$K_G = 0.7 - 1.4$ (% MW/0.1 Hz)
$K_L = 0.2 - 0.6$ (% MW/0.1 Hz)

K is within the range 0.9 - 2.0 (% MW/0.1 Hz).

As there is little data from Oman on measured values for system characteristic constants, we will use the widely-used system constant of 1.0 (% MW/0.1 Hz).

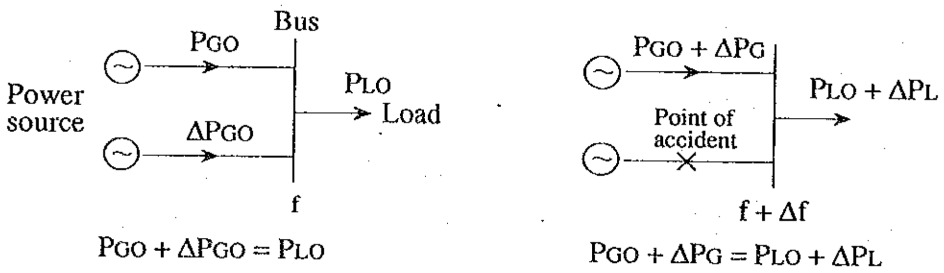
8.3.2 Frequency Fluctuations and System Operation during Power Source Tripping

(1) Frequency fluctuations during power source tripping

When the power source (generator) trips because of an accident or other factor, the system frequency drops in accordance with the power - frequency characteristics. Figure 8.3.6 indicates the frequency fluctuation Δf when the micro power source ΔP_{GO} trips from the system under the operating condition that the power source and load are well balanced at frequency f, as follows:

$$\Delta f = - \Delta P_{GO}/K$$

$K = K_G + K_L$ is the system frequency characteristic constant.



(a) Before Power Source Tripping (b) After Power Source Tripping

Figure 8.3.6 Frequency Fluctuations during Power Source Tripping

We examined the frequency characteristics for the Muscat System (current system capacity of 815 MW). If a generator of 83 MW (maximum single unit capacity of the Muscat System) trips, the frequency drop is about 1 Hz if our calculations assume K = 1.0 (% MW/0.1 Hz), or K = 81.5 (MW/Hz). We will estimate K, based on data obtained from the Rusail Power Plant operating records. A malfunction of the fire detection circuit on July 12, 1993 tripped the No. 2 gas turbine, resulting in a system frequency drop to 49.28 Hz.

Although the system capacity at that time is unknown, the peak load on that day was 786 MW. Using these data, K = 1.1 (% MW/0.1 Hz); very close to the assumed K value of 1.0 (% MW/0.1 Hz), and supporting our adoption of this value for practical use.

(2) Problems when the frequency drops

Frequency drops cause turbine blade resonance and reduce auxiliaries capacity, creating an operational continuity problem.

Turbine blade resonance occurs when there is a match between the moving blade's natural vibration and the vibration power of the working fluid which works from the turbine's nozzle to the moving blade. These resonances cause excessive stress on moving blades, resulting in fatigue-related cracking. Resonance targets the blades located in the low pressure final stage and its prior stage, where the blades are long, the inherent vibration frequency is low and low component vibrations are received. Although this point of resonance occurs at turbine start up and shut down, the exposure time is short and the turbine is not subject to load at this time, resulting in little stress and no impact on the turbine's service life.

There are no serious generator problems which directly affect unit operations. Possible generator problems include deteriorating cooling capacity as a result of auxiliaries capacity reduction, and increased excitation current for maintaining constant voltage.

(3) Operations during frequency drop

Starting up the generator which has reserve operating capacity is a strategy to regain frequency in response to system frequency drops. The operational tolerance limit is about 2.5 Hz below the rated frequency (47.5 Hz against 50 Hz). A system frequency drop during a governor-free operation requires confirmation of the load position set by the load limiter, to prevent excessive load. If set at rated load or below, operations to recover the system frequency commence when the output increase reaches the maximum, while confirming the operation status of auxiliaries.

If the system frequency drops below the turbine's allowable limit, the system is separated and switched to an independent operation. Operations must be monitored for drastic frequency and load fluctuations.

8.3.3 Phase Angle Stability

(1) Degree of phase angle stability

The degree of phase angle stability is an index of whether parallel operations can continue without out-of-step when all the system's connected generators are rotating at the synchronous speed. The generator is operated while maintaining a phase angle between the generator and the load under a steady-state operation. A disconnected power transmission lines or a rapid fluctuation in load or generator output will result in imbalance between mechanical input from the prime mover to the generator and the generator output, causing the generator to accelerate. The phase angle increases in response to the acceleration. When this angle exceeds the limit, the generator is forced to obviate parallel operations and trip from the system.

(2) Stability, system planning and operation

The degree of stability is classified into steady-state stability and transient stability, depending on the size of the external disturbance. Steady-state stability refers to the level of stable power transmission when the system is subjected to a mild load fluctuation, such as a minor disturbance. Transient stability refers to stability and power transmission during a major disturbance such as a line-to-ground fault, short circuit, disconnection, or circuit shut off.

The degree of stability is generally expressed as the upper limit of power under steady-state stability. This increases in proportion to voltage squared. At an identical voltage, the degree of stability decreases in an inverse relationship with transmission distance. The transmission capacity of power lines is often determined by stability rather than the allowable current of the electrical wires. The degree of stability is therefore a vital matter in system planning and operation.

(3) Steady-state stability and power-phase angle curve

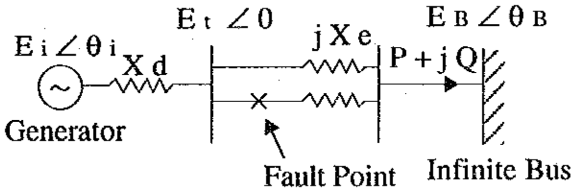
Figure 8.3.7 (a) shows a model system in which a generator with synchronous reactance Xd is connected to an infinite bus (with constant voltage and constant phase angle), through a transmission line with reactance Xe. The power P which flows through the system is calculated with the following formula:

$$P = \frac{Ei\ E_B}{Xd + Xe/2} \sin \delta$$

Power-phase angle curve (b) (P-δ curve) shows the relationship between P and δ. When $\delta = 90^\circ$ in the preceding formula, power reaches maximum, resulting in $P_{max.} = E_i E_B/(X_d + X_e/2)$, and:

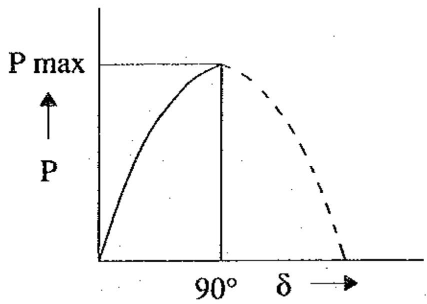
$$\frac{dP}{d\delta} = \frac{E_i E_B}{X_d + X_e/2} \cos \delta$$

This is the synchronization capacity calculated by differentiating power P from phase angle δ. The system is stable when $dP/d\delta > 0$ ($\delta < 90^\circ$), while unstable in case of $dP/d\delta < 0$ ($\delta > 90^\circ$). Figure 8.3.7(b) shows the area of stability (unbroken line) and instability (broken line).



$E_i - \theta_i$	:	Internal voltage of generator
$E_t - 0$	:	Terminal voltage of generator
$E_B - \theta_B$	:	Infinite bus voltage
$P + jQ$	:	Power and reactive power of system
δ	:	Phase angle $\delta = \theta_i - \theta_B$

(a) Model System



(b) Power-Phase Angle Curve (P- δ curve)

Figure 8.3.7 Phase Angle Stability

(4) Transient stability

Transient stability refers to the level of stability when a generator exceeds the synchronization limit for a few seconds, after an accident such as a power transmission line-to-ground fault. We assume that the line-to-ground fault has occurred at the transmission line at the point marked x on the model in Figure 8.3.7(a). We will examine the transient stability from Figure 8.3.8's P-δ curve, using the equivalent area method.

1) Pre-accident power

The P-δ curve is expressed using (1) in the Figure 8.3.8. Stable operations occur at point A, where the mechanical input and electrical output are well balanced. The pre-accident power P1 is calculated with the following formula:

$$P_1 = \frac{E_i E_B}{Xd + Xe/2} \sin \delta$$

2) Power after accident impacts are corrected

Although the post-accident, corrected operation point shifts to E on the P-δ curve (2) to resume stable operations, power drops to P_2:

$$P_2 = \frac{E_i E_B}{Xd + Xe} \sin \delta$$

3) Power during accidents

The P-δ curve becomes (3) soon after the accident. Power P_3 at that time is determined by the accident location and type. The operation point shifts to B, and as the generator is accelerated, the phase angle increases causing the operation point to shift to C.

After eliminating the effects of the accident, the point will shift along P-δ curve (2) to E. The generator's inertia makes the point move toward F. Operation will not become asynchronous and are judged stable when the area S_1 (representing acceleration energy) is smaller than or equivalent to S_2 (representing deceleration energy). This is the equivalent area method of judging operational stability.

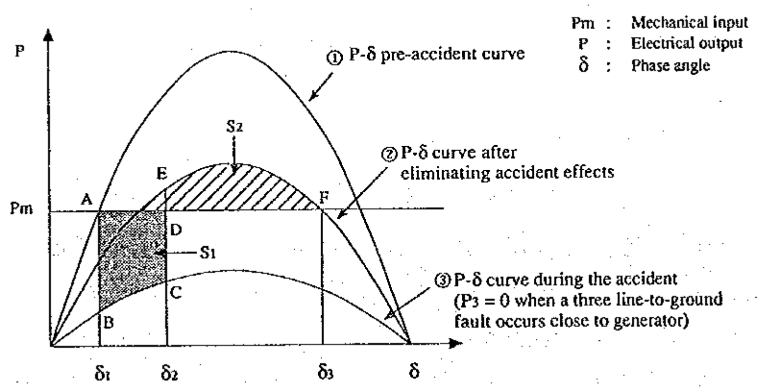


Figure 8.3.8 Determining Transient Stability using Equivalent Area Method

Figure 8.3.8 indicates that the transient stability becomes worse during accidents when there is an increase in acceleration energy or when a greater power drop in P_3 occurs. The following formula is used as an index to express the transient stability, indicating the duration of unstable operations when more time is spent on eliminating accident effects. tc represents the stability limit failure clearing time, and δc is the phase angle.

$$tc = \sqrt{\frac{2Mo\,(\delta c - \delta o)}{\pi fo Po}}$$

$$\delta c = \cos^{-1}\left\{\frac{P_{2max} \bullet \cos\delta m + PO\,(\delta m - \delta o)}{P_{2max}}\right\}$$

Where, Mo: Unit inertia constant
fo: Pre-accident frequency
Po: Pre-accident output
P_{2max}: Maximum post-accident power
δo: Pre-accident phase angle
δm: Maximum phase angle

(5) Measures to improve stability

Maintaining an appropriate degree of stability is vital to system planning. Stability study is an important part of system analysis. We will produce measures to improve stability, based on our analysis and evaluation.

We will list widely-used stability improvement measures in Table 8.3.2 for reference purposes.

Table 8.3.2 Stability Improvement Measures

Classification of Measures	Specific Measures
Reinforcing power transmission and transformation facilities	Increasing the number of parallel circuits Establishing intermediate switch yards Introducing high voltage system
Reinforcing generator control system	Quick response excitation system Power system stabilizer(PSS)
Installing special equipment	Turbine high-speed valve Serial capacitor Static var compensator (SVC) Damping resistance
Response using relay system	Adopting high-speed circuit breaker Out-of-step prevention system
Others	Equipment specifications (Impedance restriction and inertia constant increase)

8.3.4 Voltage Stability

(1) Voltage instability phenomenon

System voltage during the normal operation is maintained within predetermined values by the generator, transformer tap and phase modifying equipment. Abnormal voltage drops or increases occur when the reactive power balance cannot be maintained because of rapid load fluctuations. This is called the voltage instability phenomenon. This phenomenon is widely reported around the world, causing power failures over large areas. This Section explains the processes of this phenomenon, and suggests suitable counter measures. We would like to apply these measures as a guideline for system operations.

(2) Voltage stability (P-V curve)

For a model in Figure 8.3.9 (a), the relationship between power and voltage at the receiving end is calculated with the following formula:

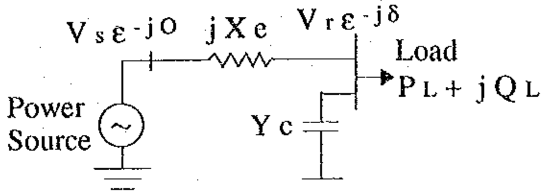
$$P_L = \frac{V_s\, V_r}{X_e} \sin\delta$$

$$Q_L = \frac{V_s\, V_r}{X_e} \cos\delta - \left(\frac{1}{X_e} - Y_c\right) V_r^2$$

If we nominate $S = \sqrt{P_L^2 + Q_L^2}$ as the apparent power, and $P_f = P_L/S$ as the power factor;

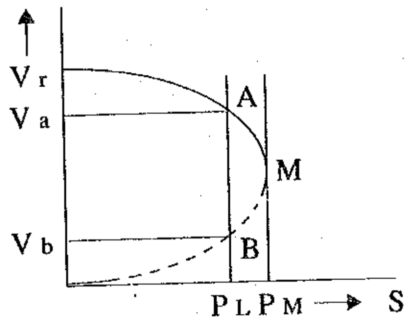
$$S^2 \pm 2S\left(\sqrt{1 - P_f^2}\right)\left(\frac{1}{X_e} - Y_c\right)V_r^2 + \left(\frac{1}{X_e} - Y_c\right)^2 V_r^4 - \left(\frac{V_s\, V_r}{X_e}\right)^2 = 0$$

The P-V curve (b) in the figure uses S as the horizontal axis and Vr as the vertical axis, based on this formula. This creates an inclined oval in contact with the horizontal axis at the point of origin.



(a) Model System

V_s : Sending end voltage
V_r : Receiving end voltage
δ : Phase angle between sending and receiving ends
P_L : Power supply to the load
Q_L : Reactive power supply to the load
X_e : Line impedance
Y_C : Admittance of capacitor



(b) P - V Curve

A : Point of stable operation
B : Point of unstable operation
M : Limit point

Figure 8.3.9 Voltage Stability

P_L and Q_L can be used to replace S in the P-V curve. Vr has two values, Va and Vb, for any given P_L. Va is the stable route, while Vb is the unstable route. Stable operations cannot occur in the range of the unstable route (indicated by dotted lines in the Figure 8.3.9 (b)).

When the load drops by ΔP or ΔQ, point A registers a load increase as a result of voltage increase, and returns to the original point A. The voltage drops further at point B, causing the load to drop and voltage instability phenomenon to occur. If left uncorrected, this will finally lead to voltage collapse.

(3) Determining stability

The unbroken lines on the P-V curve in Figure 8.3.9 indicate the area of stability. The area of instability is bounded by dotted lines. Negative dV/dP or dV/dQ values at a particular operating point indicate stable operations, while positive figures suggest unstable operations.

Voltage stability during system operation can be assessed by expressing the relationship between total power demand and system voltage, with a P-V curve based on the power flow calculations, and by calculating excess voltage capacity and excess power capacity. Excess voltage capacity is the voltage difference (Va - Vb) between A - B of Vr, which corresponds to P_L. Excess power capacity is the difference (P_M - P_L) between P_L and the limit power P_M.

(4) Maintaining voltage stability

When voltage instability phenomenon is anticipated because of insufficient excess voltage capacity or excess power capacity, the reactive power must be adjusted quickly using the generator, transformer tap and phase modifying equipment (static capacitor and shunt reactor). An effective approach is a static var compensator (SVC) which offers excellent response characteristics.

Caution must be taken during the use of static capacitor to carefully adjust the limit point as the capacitors are added, one after another, to maintain the receiving end voltage in response to increasing demand. Voltage fluctuations become significant when the capacitor's capacity increases, approaching the system voltage limit point and making it impossible to continue system operations. It is vital to monitor power flow and voltage stability of the power plant and primary substations to ensure sound system operation.

8.4 System Analysis

We will conduct a system analysis of the following matters, with a focus on the power flow calculations, in order to analyze various characteristics of the power system (power generation, transmission and transformation facilities) for this project and incorporate the results in the design. This system analysis is intended to incorporate technological examinations in the conceptual design stage. The main purpose will be to use simplified calculation methods to determine the basic characteristics and aspects of the system.

(1) Power flow and bus voltage for power transmission and transformation facilities

(2) Higher transmission voltage

(3) Capacity of interconnected transformers

(4) Degree of system stability, targeting Barka Power Plant

(5) Short circuit capacity of power transmission system

(6) Frequency drop and system operation

8.4.1 Power Flow Calculation

(1) Purpose of calculation

The power generated at the power plant travels to the load point via power transmission lines and substations. This flow is called power flow. The power flow calculation determines how much power flows into the power transmission lines and transformers, and constitutes the core of power system analysis. This calculation is vital for other applications, namely:

1) When examining the system operation method for current system fluctuations in load and power generation capacity, as well as shutting down power transmission lines; and

2) When preparing future construction and extension plans for power plants, power transmission lines and substations.

This project's power flow calculations will address the existing and future Muscat System. We will examine the capacity of static capacitor required to maintain system voltage, as well as mitigation of power transmission line load following system operations and power transmission loss.

(2) Calculation procedures

The power flow calculation is designed to determine voltage, phase angle, power and reactive power, by solving the power system equation. As shown in Figure 8.4.1, the equation is solved by repeated calculation of many non-linear, complex equations.

Flow Chart	Explanations
Input Data (1) System Configuration (2) Facility Constants (3) Operation Conditions	(1) Display connection status (generator, transformer, transmission lines and load) in the system chart, and develop it into branches (such as transmission lines) and nodes (such as buses which serve as branch connection points) (2) Produce impedance map from the system chart, and record impedance and admittance using the per unit method. (3) Nominate reactive power or reference voltage of phase modifying equipment, and power and reactive power of generators and load.
Processing (1) Solve the Power Equation	(1) Solve the power equation established for the relationship between system voltage and power flow : $\dot{I} = \dot{Y}\dot{V}$, $P + jQ = \dot{V}\bar{\dot{I}}$ Where, $\dot{I}$: Current $\dot{P}$: Power $\dot{Y}$: Admittance $\dot{Q}$: Reactive power $\dot{V}$: Voltage $\bar{\dot{I}}$: Common value for current Solve the equation via the Gauss Seidel Method or the Newton-Raphson method.
Output Data (1) Power Flow, Voltage, phase angle	(1) Calculate power, reactive power, voltage and phase angle for nodes and power and reactive power for branches.

Figure 8.4.1 Power Flow Calculation Procedures

8.4.2 Fault Calculations

(1) Objective

The magnitude of fault current resulting from line-to-ground faults, short circuits or other accidents increases when the system capacity increases or the system interconnection becomes dense, leading to facility and equipment damage. The maximum value of fault currents in each voltage class is determined by calculating the short circuit capacity when all the system's generators are operating in parallel. This calculation enables examination of the shut-down capacity.

(2) Procedures

The method of symmetrical coordinates and the Hoh-Tevnan Principle are used to calculate fault currents. The method of symmetrical coordinates classifies three phase circuits into each symmetrical circuits of zero, positive and negative phases. Each symmetrical voltage and current is calculated, and synthesized to calculate three phase voltage and current. The Hoh-Tevnan Principle expresses the circuit network as a serial circuit of no-load generator and internal impedance for any two given terminals. The principal is used to calculate the current when the impedance is connected between these two terminals. Figure 8.4.2 shows typical current calculation equations and relevant data to calculate fault currents. The basic fault current calculation formula is:

1) Three phase short circuit current

$$\dot{I}_{3LS}\,(KA) = \frac{1}{\dot{Z}_1(pu)} \times \frac{1000\ (MVA)}{\sqrt{3} \times V_b\ (KV)}$$

Where, $\dot{Z}_1$: Positive phase impedance from fault point (pu value based on 1,000 MVA)

V_b: Base voltage of the system to which fault point belongs

2) Single line-to-ground current

$$\dot{I}_{1LG}\,(KA) = \frac{3}{(2\dot{Z}_1 + \dot{Z}_O)\ (pu)} \times \frac{1000\ (MVA)}{\sqrt{3} \times V_b\ (KV)}$$

Where, $\dot{Z}_O$: Zero phase impedance from fault point (pu value based on 1,000 MVA)

Flow Chart	Explanations
Input Data (1) System Configuration (2) Facility Constants (3) Operation Conditions (4) Fault Conditions	(1), (2), (3) Use identical data as in the case of power plow calculation (4) Set the fault points and type
Processing (1) Symmetrical Circuit Configuration (2) Power Flow Calculation before the Fault (3) Calculation of Symmetrical Impedance from Fault Point (4) Power Flow Calculation at the time of Fault	(1) Produce zero, positive and negative phase circuits. (2) For positive phase circuit, calculate each system section's voltage, current and load impedance before the fault, using the normal power flow calculation method. (3) Calculate $\dot{Z}_0$, $\dot{Z}_1$, $\dot{Z}_2$, using Xd", Xd', and Xd for generator impedance, depending on the points of fault passage. (4) Structure the symmetrical circuit depending on the type of fault, then calculate the fault point voltage and current and combine this with the power flow (2).
Output Data (1) Voltage and Current at the Time of Fault	(1) Output voltage and current at the time of fault for the set fault point and for each system section

Figure 8.4.2 Fault Calculation Procedures

8.4.3 Stability Calculation

(1) Objective

Calculating the stability determines if the generator voltage can be maintained in synchronous operation, and the phase angle can be maintained against disturbances such as system load fluctuations and faults. The results of these calculations are used to structure a system where generators can continue stable functioning during steady-state operations and during transient-state.

(2) Procedures

The stability is classified into steady-state or transient stability, depending on the size of the disturbance. Some systems experience major disturbances and rapid changes in transient stability. We will examine both steady-state and transient stability.

The stability study is conducted by means of the system model comprising the generator, load and control system. The following models are used to simulate dynamic characteristics.

1) Generator model

This model is based on the basic Park formula, which considers initial transient effects (direct axis reactance Xd" and horizontal axis sub transient reactance Xq") and saliency.

2) Load model

The targeted load and load voltage characteristics are lighting load representing constant impedance characteristics and motor load representing constant KVA characteristics.

3) Control system model

This model considers such control systems as automatic voltage regulator (AVR) and governor.

In calculating stability, we assume that a three phase line-to-ground fault has occurred on the power transmission line connected to Barka Power Plant. The impact on the generator is examined by setting the following conditions:

1) Fault resistance set at 0, no high-speed reclosing of the power transmission line; and

2) Fault clearing time shall be 0.10 second on the ground that the power transmission line's main protective relay is activated properly, but with the assumption of power line carrier relay system failure resulting in 0.30 second period to eliminate accident effects by operating back-up protective relay.

The stability is determined by solving the generator's movement equation. Figure 8.4.3 shows the calculation procedures, and we will use a computer to manage many differential equations and variables, perform high speed calculations, and analyze the stability.

Flow Chart	Explanations
Input Data (1) System Configuration (2) Facility Constants (3) Operation Conditions (4) System Model	(1), (2), (3) Use data as for power flow calculation (4) Create models for generators and loads in the power system and input transient characteristics for generator movement and winding circuits of field, damper, and armature.
Processing (1) Calculate Pre-fault Power Flow (2) Calculate Initial Value (3) Calculate Circuit Constant (4) Solve Movement Equation	(1) Calculate power flow based on pre-fault system configuration, power generation and load conditions. (2) Calculate internal voltage, phase angle and generator output. (3) Calculate generator internal voltage and transmission admittance, and recalculate circuit constants for changing circuit conditions such as fault occurrence and circuit breaker switching. (4) Solve generator movement equation $\frac{Mo}{\omega n} \frac{d^2 \delta}{d t^2} = Pm - Pe$ Mo : Unit inertia constant; t : Time ωn : Rated angle speed; Pm : Mechanical input δ : Phase angle; Pe : Electrical output
Output Data (1) Output Phase Angle, etc. after Time ΔT	(1) Calculate generator phase angle when post-failure timeΔT passes (for example 0.02 seconds), repeat the step by step calculation up to the time when the calculation is concluded (for example three seconds)

Figure 8.4.3 Stability Calculation Procedures

8.4.4 Analysis of the existing Muscat system

The following general system analysis was performed to gain an indication of the power flow and stability of the existing Muscat system.

(1) Creating a Model of the Muscat System and Setting Operating Conditions

A system model requires information about the system configuration (single-line diagram), facility constants and operating conditions. Since the operating conditions vary dramatically over time, it is necessary to pinpoint the load and generating power at a common time. According to MEW operation records, a maximum power level (peak load) of 826 MW was recorded at 2:27 in the afternoon on 22 June 1993, the toughest operating conditions for the system. Creating a model of the system under these conditions and conducting simulations is a valuable way of understanding the system's features. The MEW keeps hourly records of the Muscat system's operating data (active power, reactive power, voltage, etc.) and for June 22, operating data in good enough shape to be used was available for the hours of 2:00 pm and 3:00 pm. The June 22, 2:00 pm operating data was chosen. At this point, the Muscat system was supplying a total of 785 MW, with 289 MW from the Ghubrah power station, 484 MW from the Rusail power station and 12 MW purchased from the Ministry of Defense. This level of output amounts to 96.3 % of the total facility capacity of 815 MW and demonstrates how the power stations within the system were running at close to the rated output.

The operating output of the power generators connected to the system is determined by the capability curve. However, for this system analysis, the following model was formed. The power generators at the Rusail power station not only have the largest single unit capacity, but together have a large total output. Furthermore, since the output adjustment range and output adjustment speed are also significant, the Rusail power station is assigned the task of output adjustment and can supply the necessary amount of active power and reactive power while the voltage and phase angle are kept constant. Also, the power generators at the Ghubrah power station are held at a constant voltage and a constant active power, while reactive power is supplied over a relatively wide range from a leading power factor of 0.8 to a lagging power factor of 0.8.

(2) Voltage Characteristics of the Load and Voltage Adjustment

The voltage characteristics of power loads include constant power (KVA), constant current and constant impedance characteristics. Since the relative share of each of these characteristics varies depending on the type of load and the operating conditions, it is difficult to clarify the voltage characteristics of the load. In small-capacity systems, an approximate load can be determined by the constant impedance characteristics. As systems increase in capacity, however, inverters and other power-electronics-related equipment are introduced, causing increases in the relative share of the constant power (KVA) characteristics. This in turn causes a significant drop in the stability of the system because as the constant power (KVA) characteristics of the load increase in weight, the voltage characteristics of the load become more sensitive. If power flow and stability calculations are conducted under such unstable circumstances, it is extremely difficult to determine even an approximate result. This difficulty stems from the non-linearity and the many variables of the power equation between the system voltage and the power flow and the kinetic equation for power generators when faults occur. Therefore, it is necessary to set the voltage characteristics of the load so that an approximate result can be obtained by converging the recursive calculation, which is the basis for numerical analysis.

Voltage variations which occur at points within the system result from the imbalance in generation and consumption of reactive power. To adjust the level of reactive power, field current control is applied to the power generators, and load ratio transformers (LRT), power capacitors, shunt reactors and other regulating devices are used. The conditions under which these regulating devices and equipment are operated vary constantly, and the operating conditions when the maximum power was recorded are unknown. To fill this gap, it is assumed that the voltage regulating devices were being operated to maintain the primary substation bus voltage within 5 % of the reference voltage.

(3) Results and Evaluation of Power Flow Calculations

After creating a system model and setting the operating conditions, the power flow calculation was conducted. The results and evaluation are explained below.

1) The primary substation loads were assumed to have 100 % constant power characteristics and the total power of the load was set at 776.7 MW, 481.4 MVAR. Power flow calculations show that the output of power generators supplying power to these loads was 780.3 MW, 611.9 MVAR, including power loss in the transmission lines and transformers, with the Rusail power station supplying 463.3 MW, 374.3 MVAR and the Ghubrah power station supplying 317.0 MW, 237.6 MVAR.

2) The power factor of the loads was set at 0.8. When the power factor of a load with constant power characteristics is small, the voltage drop caused by reactive power rises dramatically and the system is destabilized. In fact, when the power flow calculation is performed with the power factor set at 0.8, a voltage drop of 5 % or more is seen throughout the system. This result demonstrates the need to increase the power factor of the load in system operation. Therefore, the calculation was performed again with the power factor being reset from 0.80 to 0.85. This significantly improved the voltage drop in the buses and transmission lines. In order to maintain the power factor at 0.85 or higher during system operation, an appropriate number of power capacitors have to be installed in the substation buses. Figure 8.4.1 shows the power flow distribution obtained from the power flow calculation.

3) The operating power factor for the power generators was 0.78 for the Rusail power station and 0.80 for the Ghubrah power station, or what works out to 0.79 overall. The amount of reactive power supplied by the power generators increased and the power factor decreased because the amount of reactive power consumed by the transformers was large even with the power factor set at 0.85 for the loads.

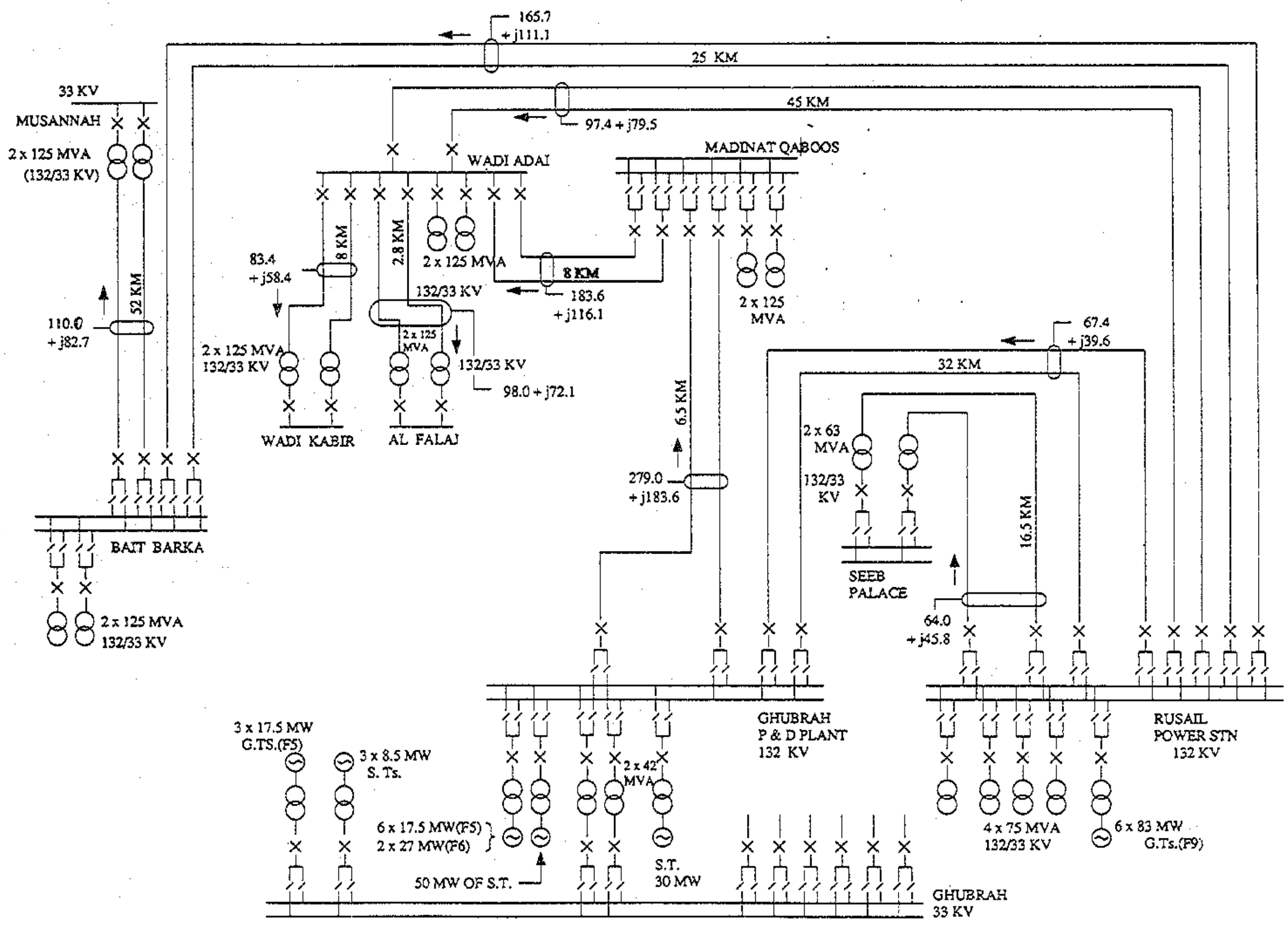
4) The voltage drop in the substation buses and in the transmission lines is significant because of the large loads at the primary substations and the medium- to long-distance transmission line connections. This voltage drop can be kept within 5 % by tap changes of the load ratio transformer (LRT), but LRT control of reactive power is inefficient. Reactive power should be generated as close to the area of consumption as possible. For this reason, it is essential to increase the capacity of power capacitors in the bus of the secondary substations in order to meet the future increase in demand.

(4) Results and Evaluation of Stability Calculations

When a power generator is dropped from the system, and even if this results in a sudden change in load, phase angle stability and voltage stability must be maintained. The stability calculation performs a dynamic simulation to gauge this capability. There are a great number of possible incidents which could be tested. For this study's purposes, a simulation is performed to determine the degree of change in 132 KV bus voltage and system frequency for a representative case in which a single generator with the maximum single unit capacity of 83 MW is tripped. The results are explained below (see Figure 8.4.2).

1) Within about 0.2 seconds following the generator trip, the bus voltage drops to around 0.87 PU (per unit)(= 132 KV x 0.87 = 115 KV), but it then recovers to 0.93 PU in approximately two seconds. However, due to the loss of reactive power supply from one generator, the bus voltage stays at 0.93 PU thereafter. This makes it necessary to install a power capacitor of appropriate capacity in order to secure voltage at 0.95 PU or higher.

2) The system frequency drops a maximum of 0.5 Hz as a result of a generator trip. If the drop is no more than 3 % (1.5 Hz) of the base frequency of 50 Hz, the impact on the turbine in operation is rather small and continuous operation of the turbine is feasible. Therefore, a frequency drop of about 0.5 Hz does not present any trouble nor does it require the activation of spinning reserve power.



LEGEND

G.T. — GAS TURBINE
S.T. — STEAM TURBINE
F 5 — FRAME 5
F 6 — FRAME 6
F 9 — FRAME 9

NOTES

1. POWER FLOW OF MAJOR TRANSMISSION LINES ONLY ARE INDICATED.
2. POWER FLOW IS EXPRESSED AS P(MW) +jQ(MVAR: LAGGING)

POWER FLOW SUMMARY

		P(MW)	Q(MVAR)
GENERATION	PV	317.0	237.6
	SWING	463.3	374.3
	TOTAL	780.3	611.9
LOAD (CONST. KVA)		776.7	481.3
TRANSMISSION LOSS		3.6	130.8

Figure 8.4.1 Power Flow for Muscat Systems in 1993

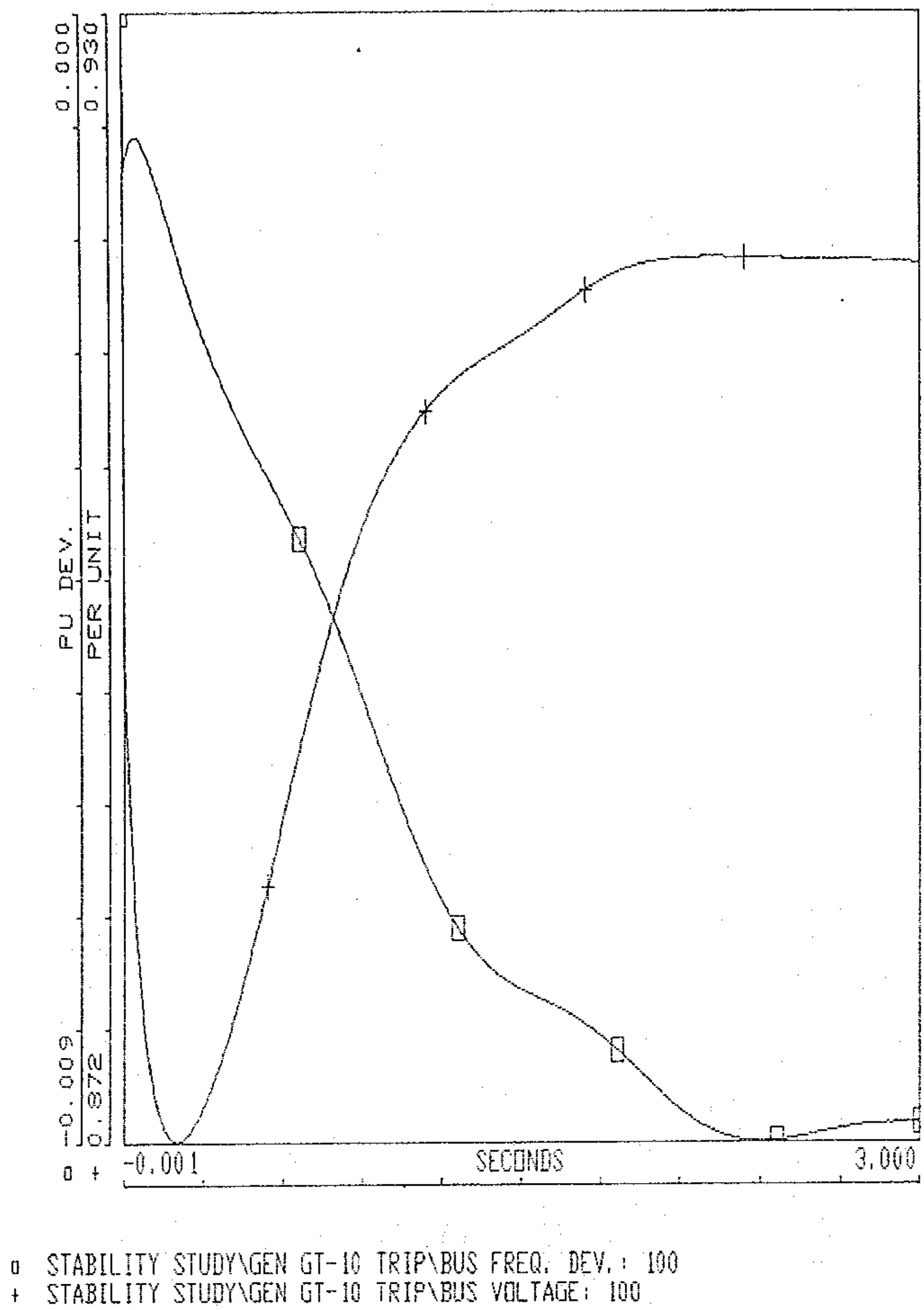


Figure 8.4.2 Dynamic Simulation for 1993 (Constant KVA Loads)

8.4.5 System Analysis for Construction of the Barka Power Plant

The power plant envisioned in this project will be connected to the Muscat system and have a total installed capacity of 1,848 MW by 2010. In this section, the results and evaluation of a general system analysis performed with the goal of understanding the power flow and stability of the system after connection of the Barka power plant are explained.

(1) System Configuration in 2010

The maximum power generated by the Barka power plant in 2010 is expected to be 1,632 MW so the sending end power will be 1,512 MW after subtracting a total of 120 MW for station consumption and desalination plant power requirements. Of this amount, 1,212 MW will be transmitted to the Muscat system and the remaining 300 MW to the Wadi Jizzi system. Furthermore, the Manah system, which according to MEW's plans will be connected to the Muscat system in 1996, has a capacity of 90 MW. This power transmission plan and system configuration are shown in Figure 8.2.2.

(2) Power Capacity and Load Model

From 1996 on, the Muscat system and Wadi Jizzi system are expected to respectively generate 1,010 MW and 278 MW of power for a total of 1,288 MW, and any power shortages will be handled by the Barka power plant. In other words, the power generators in the 1,288 MW group will supply a constant voltage and a constant active power, while the Barka generators supply necessary amounts of active and reactive power at a constant voltage and phase angle. Furthermore, the power factor of these generators will be adjustable within a range of 0.8 leading and 0.8 lagging.

The 1993 load demand and 2010 power demand forecast values are used to create a model of primary substation loads in 2010. In doing so, the increase in power demand from 1993 to 2010 in the Muscat system is distributed to each substation at the same load ratios obtained for 1993. As explained in section 8.4.4, the power factor and voltage characteristics of the load have a considerable impact on the power flow and stability calculations. To understand the general characteristics of the system, a simplified load model is necessary. Taking into account the analysis results for the Muscat system in

1993, the power factor is set at 0.95 and the voltage characteristics of the loads at constant impedance.

Also, AAAC 400 mm^2 x 4 conductors per phase will be used for the transmission lines for this project. Factoring in the voltage and surge impedance of the transmission lines, the transmission capacity will be about 800 MW per circuit. Transmission capacity through the existing AAAC 400 mm^2 x 2 conductors per phase is estimated at approximately 200 MW.

(3) Results and Evaluation of Power Flow Calculations

Figure 8.4.3 shows the results of power flow calculations when the Muscat and Wadi Jizzi systems are interconnected. As shown in this figure, the load is 2,307 MW, 752 MVAR and transmission loss is 169 MW, 886 MVAR. By comparison, the existing power plants supply 815 MW, 368 MVAR and the Barka power plant supplies 1,661 MW, 1,270 MVAR.

The transmission loss of active power from the power plants to the 33 KV secondary substations was calculated at 6.8 %.

The transmission and distribution loss in the Muskat system in 1993 is estimated at 12 %, with the transmission loss for that period accounting for less than half. When it is completed in 2010, the interconnected system is expected to be notably larger than the current system, resulting in a much greater transmission loss due to heavy flow. Given this, it is possible to infer that the transmission loss of 6.8 % will closely reflect the actual situation.

In terms of reactive power, the transmission loss was calculated at 54.1 %. This loss was due to LRT tap changes in response to the voltage drop in the buses and transmission lines stemming from a demand for load reactive power. These changes resulted in a large flow of current and a significant increase in the loss of reactive power in the transformer and the transmission system. The reactive power became larger with the increase in active power because the load was large despite the load power factor being set at 0.95. There are various methods for adjusting this reactive power, including LRT, power capacitors and the application of field current control to the power generators. The most effective method for minimizing transmission loss must be selected. As mentioned in 8.4.4(3), the best way to control voltage and reactive power is to establish power capacitors in the buses of the secondary substations. This greatly reduces transmission loss. Furthermore, the load power factor can be expected to improve through the use of power capacitors, making it essential that phased capital investment be implemented in order to obtain a target power factor of 0.95 or higher in the future system.

In the interconnected system, the largest flow, 732.3 MW, will pass through transmission lines running between the Barka power plant and the Bait Barka substation. There will be two transmission line circuits with a transmission capacity of 800 MW each. This is considered to be sufficient to meet the estimated flow. The power flow in the transmission lines forming an interconnection to the Wadi Jizzi system will be 314.5 MW. For this, two 220 KV lines will be adequate.

However, the long transmission line distance of 180 km results in an enormous transmission loss measuring 49.7 MW (15.8 %). For this reason, it is not advisable to cover the shortage of power in the Wadi Jizzi system entirely by the Muscat system. In consideration of the purpose of system interconnection, the practical approach to covering the shortage in the Wadi Jizzi system is to increase the number of generators of appropriate capacity at the Wadi Jizzi power station.

The Manah system will have facilities with a capacity of 90 MW, but engenders a large transmission loss being located at a distance 90 km away from the Rusail power station. Therefore, as in the Wadi Jizzi system, the best approach to covering the shortages expected in the Manah system is also to strive to increase the number of generators within the system.

(4) Results and Evaluation of Stability Calculations

Figure 8.4.4 indicates the transient response when a power source corresponding to the supply reserve margin of 150 MW at the Barka power plant is lost. The results of conducting a dynamic simulation for three seconds following a generator trip shows that within 0.6 seconds, there is a state of damped oscillation. Therefore, this system is considered to be stable.

The bus voltage at the Barka substation (220 KV) drops to 0.95 PU following the generator trip, but it then gradually recovers to the reference voltage range. The drop in system frequency stays at 0.3 % and does not present any trouble in terms of system operation.

(5) Voltage Characteristics of Power Loads

Flow and stability calculations were conducted assuming that the system to be completed in 2010 would have a load with constant impedance characteristics. This is because under a load of constant power characteristics, the calculations do not converge and the system becomes unstable. To overcome these unstable conditions, there is a need to implement the measures described in item 8.3.4.

Figure 8.4.5 shows the results of calculations assuming a load for constant current characteristics, which lies between constant impedance and constant voltage characteristics. There is a close resemblance to Figure 8.4.4, and while the time constant is similar, the amplitude is small. The value of the constant β for the voltage characteristics of the system for this project (see item 8.3.1) cannot be specified, but in terms of voltage stability, if the system is operated under the conditions $\beta \geq 1$, it is assumed that system stability will be secured.

(6) Capacity of the transformer for interconnection

The results of power flow calculations indicate that the most appropriate capacity of transformers for interconnection is as follows. (These capacities are reference figures and may be subject to change depending on the future system structure and operation methods.)

- Between the Barka substation and the Bait Barka substation: 450 MVA x 2 banks
- Between the Barka substation and the Madinat Qaboos substation: 250 MVA x 2 banks

(7) System Analysis Accompanying the Beginning of System Operation in 1998

The Barka power plant will be constructed in phases with two open-cycle gas turbines to begin operation in 1998. Power flow calculations show that 160.9 MW will flow through the transmission lines with a distance of 15 km between the Barka power plant and the Bait Barka substation, and that both transmission loss and voltage decrease will be approximately 1 %. This presents no trouble in terms of transmission lines. However, in the transmission and transformation facilities, the increase in demand over the period from 1994 to 1998 will result in a flow of active and reactive power that will greatly increase the voltage drop and transmission loss in comparison with the system structure in 1993. The power factor improvement from the use of power capacitors and the supply of reactive power will become increasingly important.

In terms of stability calculations, the bus voltage and frequency of the 132 KV Ghubrah substation was measured when one of the gas turbines at the Barka power plant was tripped. Both the bus voltage and frequency decreased temporarily, but recovered within a few seconds.

(8) Summary of Power System Analysis

The results of the power system analysis of this project is summarized as follows:

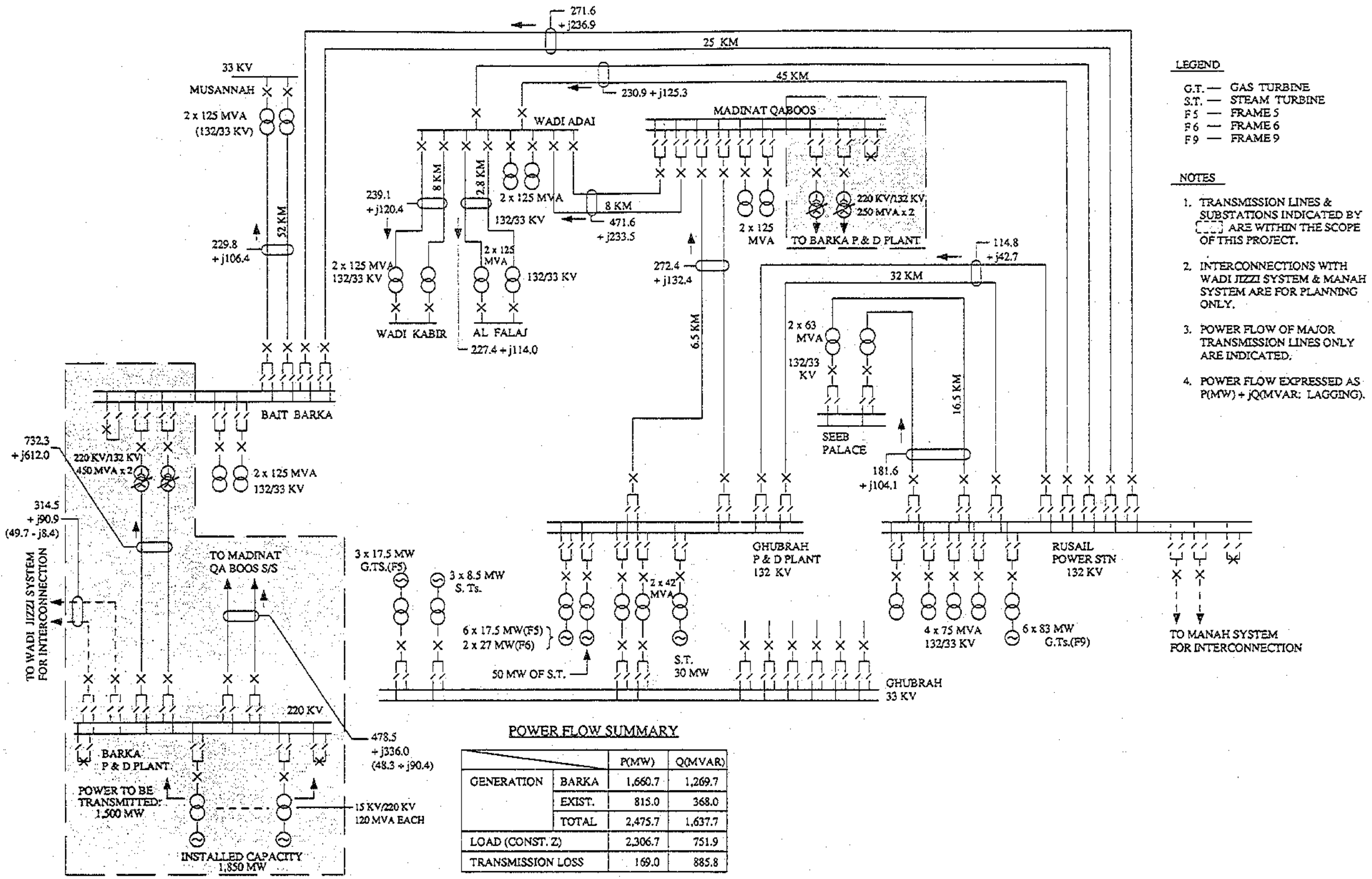
1) The transmission voltage of 220 kV is considered to be appropriate for the transmission lines between the Barka power plant and Bait Barka and Madinat Qaboos substations.

2) As the power demand increases, it is expected that the existing transmission and transformation facilities will be faced with surging power losses and voltage drop. Installation of power capacitors will be needed to eliminate those troubles.

3) For the interconnection with the Wadi Jizzi system, the transmission voltage of 220 kV is considered to be appropriate. It is desirable, however, that any shortage in the supply capacity for this system be supplemented by installing additional generators in the system.

4) An interconnection with the Manah system by the 132 kV transmission lines is being planned by MEW. The voltage will not present any trouble in the system operation for a transmission capacity of 90 MW.

As the load demand increases, the power system increases in capacity, causing the power flow and voltage of the system to constantly vary. The results obtained through the power system analysis for the changing system represent the approximate behavior of the system at a certain point. System analysis methods such as power flow calculation and stability study are indispensable tools for the planning and operation of the power system and should be continuously used for the efficient operation of the Muscat and Wadi Jizzi systems.



POWER FLOW SUMMARY

		P(MW)	Q(MVAR)
GENERATION	BARKA	1,660.7	1,269.7
	EXIST.	815.0	368.0
	TOTAL	2,475.7	1,637.7
LOAD (CONST. Z)		2,306.7	751.9
TRANSMISSION LOSS		169.0	885.8

Figure 8.4.3 Power Flow for Muscat & Wadi Jizzi Systems in 2010

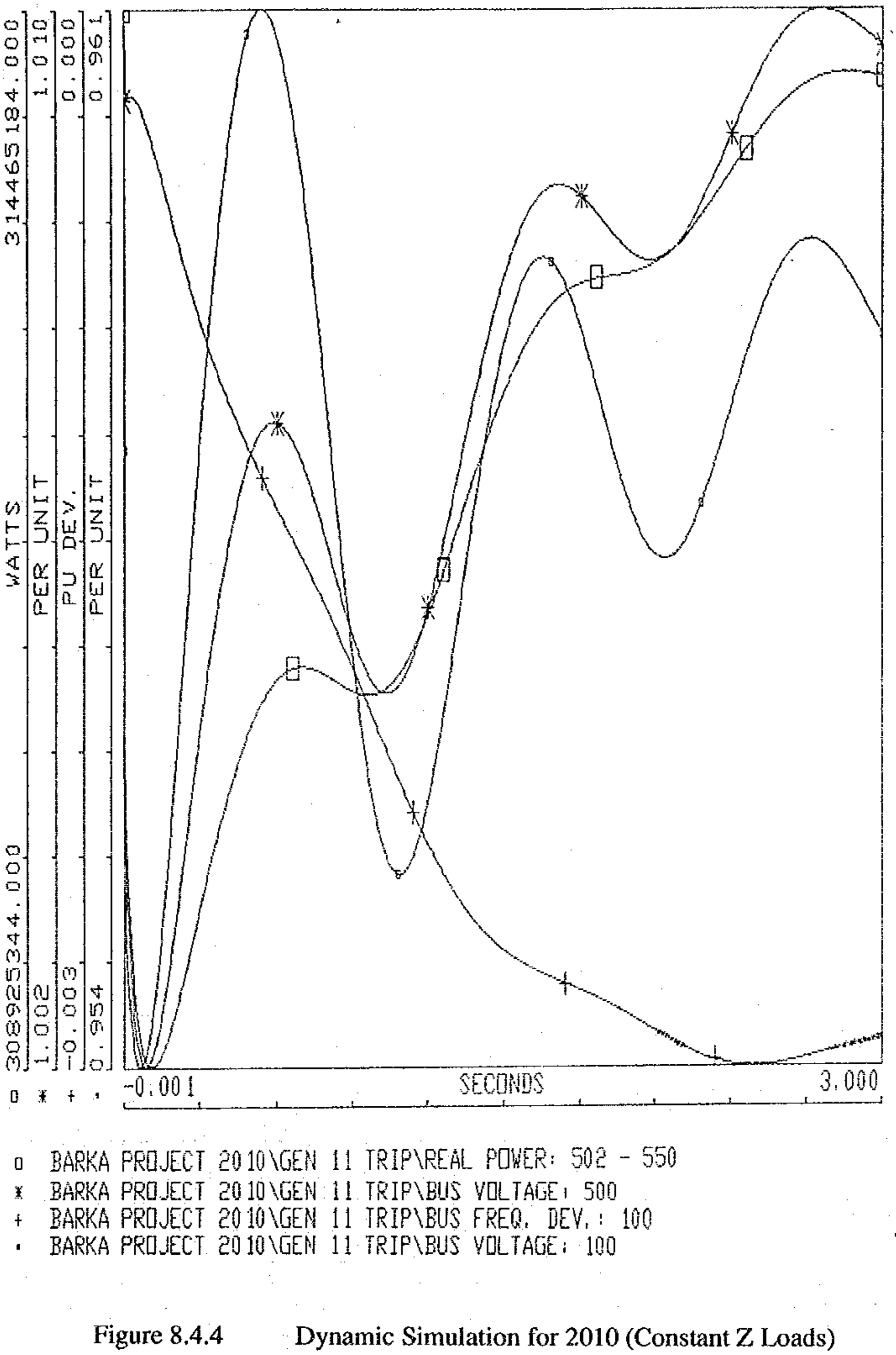


Figure 8.4.4 Dynamic Simulation for 2010 (Constant Z Loads)

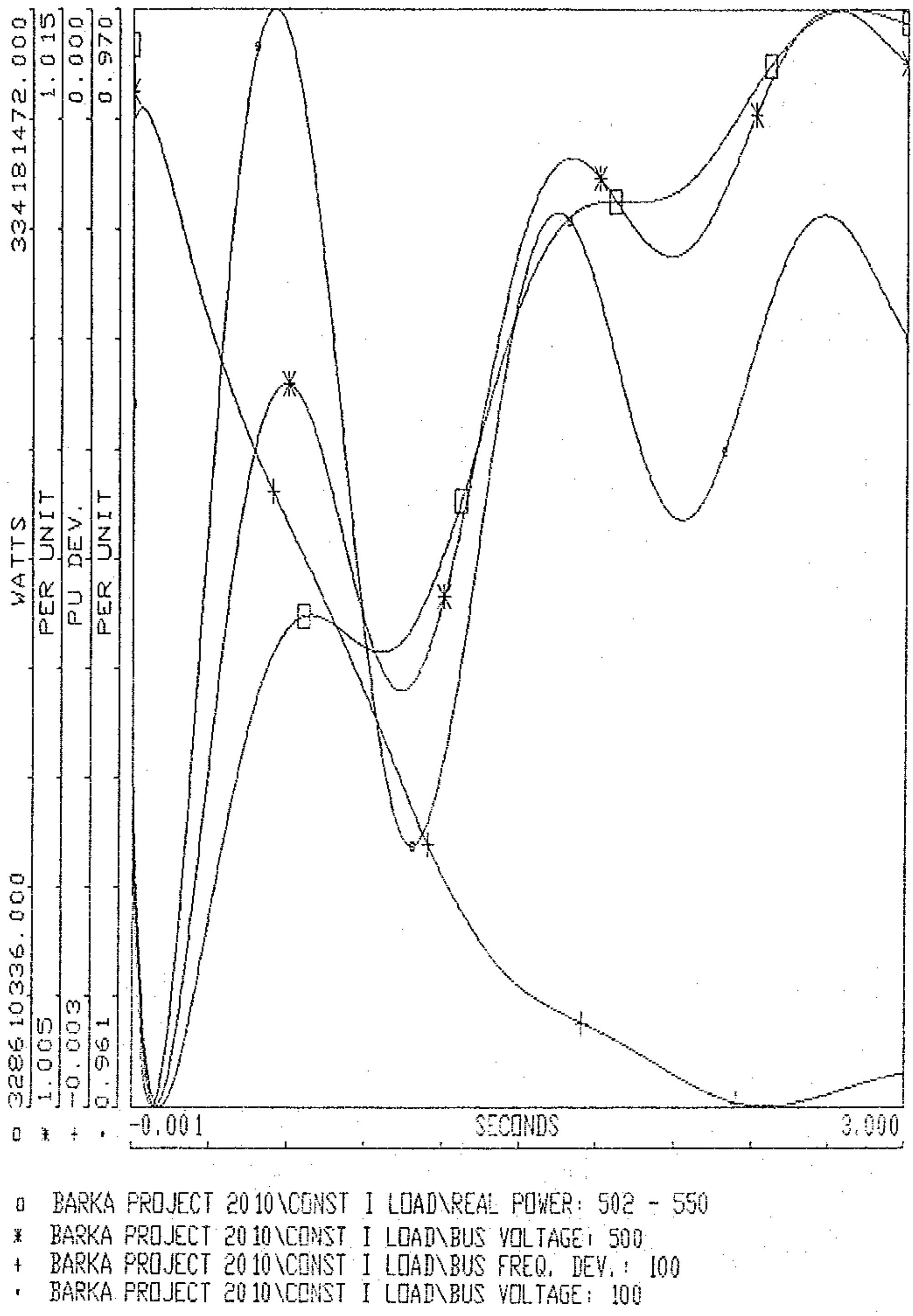


Figure 8.4.5 Dynamic Simulation for 2010 (Constant I Loads)

8.5 Power Transmission Facilities

We examined the design and materials specifications for the overhead power transmission lines which form the core of the power transmission facilities, and set the specifications as follows.

8.5.1 Insulation Design

(1) Design policy

Abnormal voltage is given considerable weight in designing the power transmission system insulation, and is classified as either:

1) High voltage but relatively short duration abnormal voltage, such as lightning or travelling wave; or

2) Switching surge and intermittent arc line-to-ground fault abnormalities caused by attenuating vibrations. Abnormalities such as sound phase voltage increase during line-to-ground faults have a frequency close to standard levels, and continue for a relatively long time.

As 1) is caused by external factors, it is called external abnormal voltage (or external lightning), while 2) originates from within the system, and is known as internal abnormal voltage (or internal lightning). Insulation design must combat these abnormal voltages after considering three factors: (a) Type and magnitude of abnormal voltage; (b) Restriction voltage value (protection level) of protective devices such as lightning arrestors; and (c) Insulation strength of equipment. The basic concepts behind insulation design are:

1) Protection of equipment insulation against external lightning; and

2) Insulation of each section of the system to sufficiently withstand internal lightning.

Poor coordination of the insulation levels required by 1) and 2) may result in the undesirable situation of frequent failure of equipment with lesser insulation strength. It is vital to attempt rational coordination of insulation strength for the entire system, by appropriately selecting the withstand voltage level for each component, while considering the protection level of the protective device. Effective implementing insulation coordination will ensure safe and economical insulation design.

(2) Insulation design for power transmission line

Insulation design for overhead power transmission lines should prevent flashover accidents resulting from internal lightning. The anti-lightning design of overhead lines shall minimize the frequency of lightning-related accidents. Where accidents are inevitable, the electrical effect on the system shall be minimized by adopting a high-speed reclosing system or installing an arcing horn. These measures will prevent damage to facilities. Figure 8.5.1 shows the requirements for insulation design to manage internal lightning.

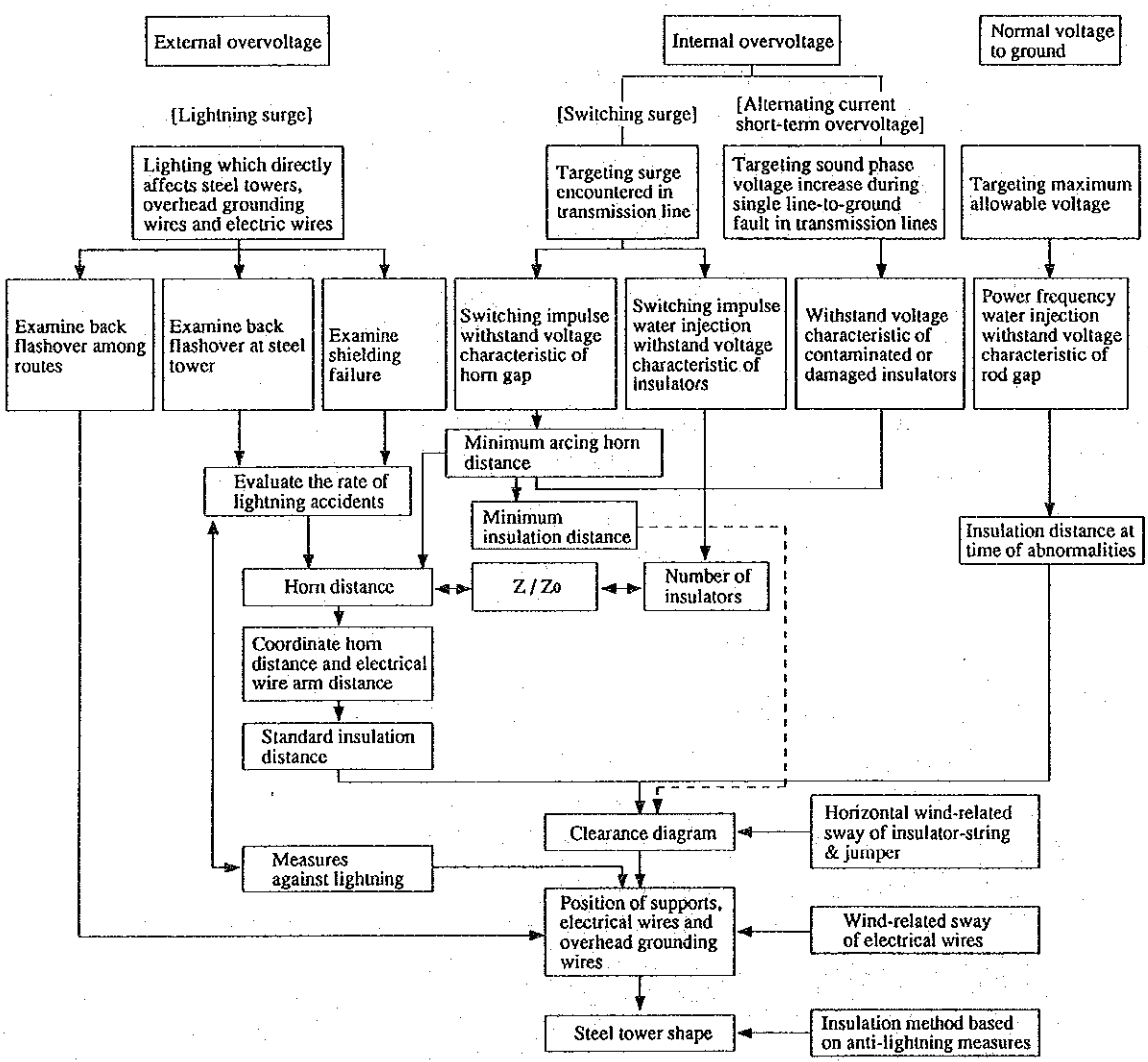


Figure 8.5.1 Insulation Design Procedures for Power Transmission Lines

8.5.2 Insulation Design Data

(1) Internal abnormal voltage

The type and level of abnormal voltage (internal lightning) encountered within power transmission systems are as follows:

1) Line switching abnormal voltage (switching surge)

Power transmission systems of ≥ 132 KV use neutral direct grounding systems. This creates effective grounding for a three phase power system, where the sound phase voltage to ground at the time of a single line-to-ground fault does not exceed 80 % of the normal line-to-line voltage. As abnormal voltage when the charging current is shut off at non-load is about 2.8 times the normal voltage to ground on the effective grounding system, we will use this value as the peak voltage to ground.

2) Transient abnormal voltage during failure

The sound phase starts to show transient abnormal voltage during continuous line-to-ground faults. The sound phase voltage to ground is between 1.5 and 2.5 times the normal voltage to ground, but attenuates in a short time.

3) Continuous abnormal voltage during system operation and during failure

The Ferranti effect and the generator's self excitation phenomenon cause the voltage to increase, creating continuous abnormal voltage of about 0.8 times the maximum operating voltage.

(2) Maximum operating voltage

The maximum operating voltage is the limit of voltage increase during light load or no load. The maximum operating voltage used to select insulation distance is 1.2/1.1 times the nominal voltage for 275 KV. We will set the voltage stipulated in the IEC standards for 220 KV and 400 KV.

(3) Corrective coefficient for atmospheric conditions

Flashover voltage is based on standard atmospheric conditions (20°C temperature, 760 mmHg atmospheric pressure and 11 g/m^3 humidity). A corrective coefficient of 1.2 will be used for this project, as construction conditions will vary from standard conditions.

(4) Creepage distance

The insulator creepage distance (minimum distance between upper conductor and lower conductor in the direction of the insulator surface) shall be 45 mm/KV, based on OES 32. A 245 KV maximum operating voltage will have a creepage distance of 11,025 mm.

(5) Ground insulation distance

The insulation distance between electrical wires and supports (the steel towers) can be determined by two standard methods:

1) Standard insulation distance - the distance which prevents flashover between supports and electrical wires, even when there is no wind and the overhead grounding wire or steel tower is directly struck by external lightning; or

2) Minimum insulation distance - the distance which prevents internal lightning flashover between support and electrical wire, even when wind causes the electrical wire to sway horizontally.

The ground insulation distance should be based on the flashover characteristic of the rod gap, with 50 % impulse flashover voltage applied to 1) and dry flashover voltage (water injection flashover voltage for the voltage ≥ 275 KV) applied to 2). Calculate the required air gap distance. Switching surge (internal lightning) shall be used as the abnormal voltage in selecting insulation distance, since it poses a greater threat to power line insulation than does external lightning.

Table 8.5.1 shows the insulation design details and results.

(6) Clearance diagram

As an example, we will take the suspension type steel tower and determine the insulation distance between electrical wires and supports, based on insulator length and distance.

1) The standard insulation distance shall be taken up to a 20° horizontal sway

angle for a suspension insulator.

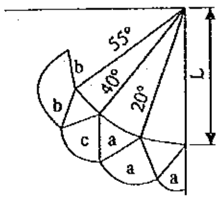
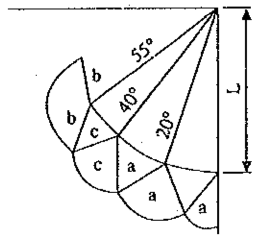
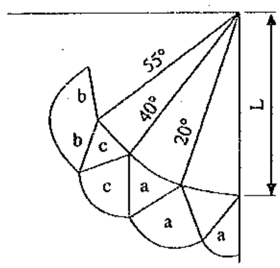
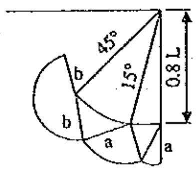
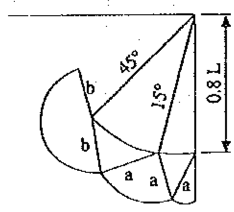
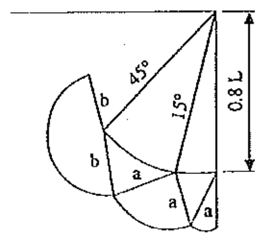
2) The average of standard insulation distance and minimum insulation distance shall be taken between the horizontal sway angle of 20° and 40°.

3) The minimum insulation distance shall be taken when the horizontal sway angle is between 35° and 40°.

Figure 8.5.2 shows a clearance diagram produced in this manner.

Table 8.5.1 Insulation Design

No.	Design items			Nominal voltage (KV): N		
				220	275	400
1.	Switching surge withstand voltage					
	(1) Maximum operating voltage	: Um	(KV)	245	300	420
	(2) Peak value of voltage to ground	: $Um \times \sqrt{2} / \sqrt{3}$	(KV)	200	245	343
	(3) Multiplier for switching surge abnormal voltage	: n		2.8	2.8	2.8
	(4) Switching surge voltage	: $Um \times \sqrt{2} / \sqrt{3} \times n$	(KV)	560	686	960
	(5) Corrective coefficient for elevation, etc.	: k		1.2	1.2	1.2
	(6) Required switching surge withstand voltage	: (4) x k	(KV)	672	823	1,152
2.	Power frequency withstand voltage					
	(1) Multiplier for power frequency abnormal voltage	: n'		0.8	0.8	0.8
	(2) Continuous abnormal voltage	: Um x n'	(KV)	196	240	336
	(3) Corrective coefficient for elevation, etc.	: k		1.2	1.2	1.2
	(4) Required power frequency withstand voltage	: (2) x k	(KV)	235	288	403
3.	Salt contamination withstand voltage					
	(1) Creepage distance	: 45 mm/KV (between lines)	(mm)	11,025	13,500	18,900
	(2) Required number of long rod insulator strings, with figures in brackets showing creepage distances insulator strings	210 KN (4,100 mm)		3	4	5
4.	Standard insulation distance					
	(1) Switching surge withstand voltage: as per 1. (6)		(KV)	672	823	1,152
	(2) Required air gap length		(cm)	156	197	305
	(3) Standard insulation distance		(cm)	160	200	305
5.	Minimum insulation distance					
	(1) Switching surge withstand voltage: as per 1. (4)		(KV)	560	686	960
	(2) Corrective coefficient for elevation, etc.	: k'		1.1	1.1	1.1
	(3) Required withstand voltage		(KV)	616	755	1,056
	(4) Required air gap length		(cm)	140	177	274
	(5) Minimum insulation distance		(cm)	140	180	275
6.	Minimum insulation distance between phases					
	(1) Peak voltage to ground		(KV)	200	245	343
	(2) Multiplier for switching surge (between phases)	: n"		4.5	4.5	4.5
	(3) Maximum surge voltage (between phases)		(KV)	900	1,103	1,544
	(4) Required withstand voltage		(KV)	970	1,214	1,698
	(5) Required insulation distance		(cm)	210	280	435

Nominal Voltage	220 KV	275 KV	400 KV
Suspension Tower			
Tension Tower			
a	160	200	305
b	140	180	275
c	150	190	290
L	390	520	650
0.8L	320	420	520

a : Standard insulation distance (cm)
b : Minimum insulation distance (cm)
c : Mathematical average of a and b
L : Length of insulator strings (cm)

Figure 8.5.2 Clearance Diagram

8.5.3 Design to Combat Salt Dust Contamination

The sites of this project's power transmission and transformation facilities experience only a small annual average rainfall, but are exposed to fairly strong seasonal winds, high temperatures and high summer humidity. These meteorological conditions place extremely severe demands on insulators, necessitating careful insulator selection.

Industrial contamination from exhaust gas, soot and dust, as well as adherence of wind-borne salt, cause contaminant flashover on insulators. A rational and economical combination of methods shall be applied to prevent contaminant-related accidents. The following methods are believed to prevent this type of damage.

(1) Special insulators for salt dust protection

Insulators need to minimize flashover and contamination damage by:

1) Creating a smooth surface with excellent rain washing effect to prevent salt dust adherence; and

2) Incorporating long creepage distances and large surface leakage resistance to prevent leakage current from circulating.

Fog insulators or long-rod insulators fulfill these requirements. While deep-folded fog insulators are effective against rapid contamination or damage caused by short bursts of seasonal wind, they are subject to salt dust accumulation in the long-term.

(2) Over-insulation system

Using the internal lightning voltage as a standard, the expected maximum voltage is set at 2.8 times the phase voltage (for effective ground system). The water injection status is considered as the normal worst case condition for insulators. The number of insulators for each string is based on the water injection flashover voltage for the string. When a water injection flashover voltage for only one insulator is string, we consider the appropriate efficiency for an insulator string. The over-insulation system refers to suppression of effect of salt dust by increasing the number of insulators by one to four, depending on the anticipated degree of salt damage.

(3) Insulator hot line washing device

All outdoor insulators shall be fitted with an insulator hot line washing device to remove adhered salt dust. This system uses water released from a nozzle at a pressure of 2-4 kg/cm^2 and flow rate of 50-80 l/min.

The specific salt damage protection methods to be implemented for this project will be based on the above guidelines and insulators in particular will be designed as follows:

(1) Aerodynamic insulator

While fog type insulators could be adopted to reduce the cost of supports (towers) by shortening the length of an insulator string, this type of insulator is not used in Oman. Fog type insulators are not very effective in solving salt dust accumulation, contamination and damage problems . We therefore recommend aerodynamic insulators which prevent such damage, and which are widely used in the Middle East.

The aerodynamic insulator discourages salt dust adherence. It also exhibits self-cleaning properties which tend to allow any adhered material to blow away with the wind.

Long-rod insulators or suspension insulators would be suitable, and have the following characteristics.

1) Characteristics of long-rod insulators

(i) These column-shaped magnetic bodies cause corona discharge between sheds, creating uniform voltage allocation (called multi-stage division effect). This prevents electrical permeation distraction from occurring.

(ii) Flashover or damage from contamination is unlikely to occur, as the creepage distance is long and the entire magnetic body is washed by rain.

(iii) It is rare for an arc to entwine with insulators during flashover, because the insulators are long and there are no metal fixtures between them. This simplifies arcing horn design.

(iv) The slow aging process reduces maintenance.

2) Characteristics of suspension insulators

(i) Changing the number of insulators in the string enables them to respond to any transmission voltage or tension load.

(ii) Individual insulators can have a common nominal voltage, necessitating a smaller number of spare insulators than that required by other single insulators, thereby reducing spare parts expenses.

(iii) As all insulators in the string rarely fault at the same time, adding one or two insulators to the design calculation value will boost reliability significantly.

Conditions which insulators must meet are:

(i) Light weight and high mechanical strength;

(ii) Excellent electrical insulation characteristics, including preventing corona discharge;

(iii) Simple maintenance, and durability over time, with minimal changes in quality; and

(iv) Low cost.

Both long rod and suspension insulators meet these technical requirements. Long-rod insulators excel in terms of anti salt dust design, and the Oman Standards OES 32 stipulate the adoption of long-rod insulators. Aerodynamic long-rod insulators are therefore recommended for this project.

(2) Degree of insulator contamination

When salt dust contaminated or damaged insulators are moistened by rain, the electrolytic components in the sea salt and dust dissolve, creating a conductive film. This significantly decreases the insulation characteristics of the insulator surface. Understanding the degree of insulator contamination and damage is crucial in selecting insulators.

The quantity of equivalent salt component is measured on a pilot insulator to investigate the degree of insulator contamination and damage. The density of adhered equivalent salt component is obtained from the equivalent salt portion divided by the insulator surface. This is used as a guide to classify contamination and damage. The projected maximum value for rapid contamination and damage within ten kilometers of the coastline is 0.25 mg/cm^2, and 0.5 mg/cm^2 for a distance of three kilometers or less.

The adhesive density of dust on insulators in desert regions is greater than that in areas contaminated by salt dust. Coastal desert regions are exposed to both sea salt and dust, and may have values exceeding 1.0 mg/cm^2. This imposes severe demands on insulators. The power transmission lines and substations for this project will mostly be built within ten kilometers of the coast. Using a pilot insulator to evaluate the impacts of salt dust on insulators is therefore a vital part of the insulator design process.

8.5.4 Anti-lightning Design

(1) Concepts

Anti-lightning design protects the power transmission lines from lightning, and is based on two strategies, namely:

1) Preventing lightning from directly striking the power transmission lines; and

2) Restricting the increase in ground electric potential as a result of lightning current.

Shielding using overhead grounding wires addresses point 1), while reduction of tower ground resistance (counterpoise) achieves 2). Adoption of an arcing horn shall be considered to prevent damage to electrical wire and insulator during back flashover.

(2) Lightning days per year (IKL)

The strength and frequency of lightning attacks are the parameters for anti-lightning design. These are expressed as lightning days per year (Isokeraunic Level : IKL). The Muscat region has an IKL of 20. A review of recorded lightning arrestor counter at the Muscat System's primary substation supports the adoption of this IKL value.

(3) Overhead grounding wire

An overhead grounding wire is installed to shield power transmission lines to protect them from lightning strokes. This wire also reduces peak values of abnormal voltage resulting from induction lightning. A smaller shielding angle is required to ensure that an overhead grounding wire has a 100 % lightning shielding rate. Therefore, a two overhead grounding wire system is recommended. After considering mechanical and electrical requirements, we use a corrosion resistant, aluminum clad steel wire with a nominal sectional area of 110 mm^2.

(4) Counterpoise

Even when the power transmission lines are totally shielded by the overhead grounding wires, a lightning stroke to the tower or overhead grounding wire will raise electric potential, and may result in back flashover on the electrical wire. If the insulator voltage for the directly struck tower is greater than the insulator's flashover voltage value, it causes back flashover. The voltage imposed on the insulator is proportional to the tower's ground resistance. Setting a low ground resistance will effectively reduce the tower's electrical potential. This is done by embedding a copper grounding rod or a copper bar type counterpoise in the ground to achieve appropriate ground resistance. When the impulse current flows, the voltage imposed on the soil exceeds 6 - 10 KV/cm, triggering the electricity discharge of the soil. It is vital to measure the soil's inherent resistance during the design stage to prevent destructive electrical discharge and to ensure an effective grounding plan.

8.5.5 Anti-vibration Design

Measures against wind-related vibration are the core of anti-vibration design. These aeolian vibrations may cause a cut in the strand or a disconnection of the electrical wire, and accelerate the mechanical fatigue process in an insulator's metal fixtures. An air vortex develops in an electrical wire's upper wind stream when relatively mild and uniform wind hits the wire. When an electrical wire is subjected to both upward and downward periodic and alternating stress, the wire's inherent frequency and frequency of vibrations correspond with each other to create a resonance status that develops into constant vibration.

Measures to combat wind-related vibrations are to absorb vibration energy through anti-vibration devices, such as stock bridge dumpers, or reinforce the electrical wire's clamp section with armour rod, as this area tends to accumulate vibration-related fatigue. It is possible to create an effective anti-vibration design by applying these methods to single conductors.

In addition to wind-related vibration, subspan vibration can cause problems for double and multiple conductor transmission lines. This phenomenon occurs when the wind-related alternating stress vibration rate corresponds with the electrical wire's inherent vibration rate within the same subspan (the distance between two spacers within one phase). This causes problems such as phase-to-phase short circuit. Appropriate spacer distances avoid subspan vibrations.

8.5.6 Electrical Wires

(1) Electrical wire specifications

Power transmission lines must ensure:

1) High conductivity;
2) High mechanical (tensile) strength;
3) Great durability (particularly corrosion resistance);
4) High elasticity;
5) Light weight;
6) Easy installation; and
7) Low cost.

Electrical wires which fulfill these requirements include all aluminum alloy conductor (AAAC), aluminum clad steel reinforced wire (ACSR), and hard copper stranded wire. AAAC is already used for existing 132 KV power transmission lines in Oman, and is well suited to local meteorological and environmental conditions because of its excellent mechanical strength and corrosion resistance. AAAC is recommended for this project. The mechanical and electrical characteristics of AAAC are as per IEC 208.

(2) Selection of electrical wire size

Electrical wire size shall be selected after comprehensively examining such factors as stability limit power transmission capacity, mechanical strength, continuous allowable current and voltage drop. The following size is selected based on the stability limit power transmission capacity and continuous allowable current.

1) Electrical conditions

Power transmission capacity:	1,200 MW
Maximum service voltage:	245 KV, 300 KV, 420 KV
Allowable conductor temperature:	90°C

2) Atmospheric conditions

Design temperature:	50°C
Design wind velocity:	0.5 m/s
Sunshine:	1,200 W/m^2

3) Calculation of size based on stability limit power transmission capacity

The stability limit power transmission capacity Pm is proportional to the square of power transmission voltage and inversely proportional to the power transmission distance. Pm is calculated with the formula:

$$Pm = \frac{k(V[kV])^2}{L\ [km]}\ (MW)$$

k refers to the coefficient of steady-state stability transmission capacity, and equals the short circuit rate (SCR)/x (Ω/km). Using this formula for a generator SCR of 0.5, power transmission line positive phase reactance of x = 0.4 Ω/km, k = 1.25 (= 0.5/0.4), V = 245 kV, and L = 60 km, we obtain Pm = 1,250 MW/circuit. P = 1,000 MW/circuit is further obtained for a power transmission capacity in consideration of 80 % of Pm.

4) Size calculation based on continuous allowable current

The continuous allowable current for the electrical wires is calculated with the following formula:

$$Ic = \sqrt{\frac{K \cdot \pi \cdot D \cdot \theta}{\beta \cdot Rdc \times 10^{-5}}}$$

Where, Ic: Continuous allowable current (A)
K: Heat release coefficient
D: Outside diameter of electrical wire (cm)
θ: Temperature increase in electrical wire when compared with ambient temperature (°C)
β: AC - DC resistance ratio
Rdc: DC electric resistance at the nominated temperature (Ω/km)

Calculating for 400 mm² of all aluminum alloy conductor (AAAC) reveals Ic = 602 A. For a power transmission voltage of 245 KV, the rated current when a 1,200 MW transmission capacity is allocated equally to each of two transmission line circuits located on the tower is:

$$I = \frac{P}{\sqrt{3} \times V \times \cos\theta} = \frac{600 \times 10^6}{\sqrt{3} \times 245 \times 10^3 \times 0.8} = 1{,}767\ A$$

Where, I: Current (A)
P: Power (= transmission capacity) (W)

V: Voltage (transmission voltage) (V)

cos θ: Power factor

There shall be three conductors per phase, based on 1,767/602 = 2.9.

5) Selecting sizes

Based on the calculation of sizes using stability limit power transmission capacity, a single circuit can transmit 1,000 MW if the power transmission voltage is 245 KV. This does not cause any stability problems, but does necessitate three conductors per phase when the transmission capacity of 600 MW per circuit is transmitted at a voltage of 245 KV, because the continuous allowable current for 400 mm^2 of AAAC is 602 A.

(3) Dip in electrical wires

The dip - tension curve graph is produced by calculating the span, dip and tension at each temperature, using average temperatures as standards. Based on this graph, we can examine the appropriate tension at anticipated temperatures for the nominated span.

We will ignore the elongation of electrical wires relating to linear expansion coefficient and elasticity coefficient and assume that the level elevation of the support is the same, then perform the following calculation:

Formula $D = \frac{WS^2}{8T} = \frac{2.81 \times 350^2}{8 \times 4{,}516} = 9.5$ m

Where, D: Dip (m)

W: Synthesized load of electrical wire weight and wind pressure load (kg/m)
Electric wire weight 1.10 kg/m
Wind pressure load 2.59 kg/m
Synthesized load 2.81 kg/m (= $\sqrt{1.10^2 + 2.59^2}$)

S: Span (m) Standard distance of 350 m

T: Horizontal tension of electrical wires (kg)
Using AAAC of 400 mm^2
Tension load: 11,290 kg
Safety factor: 2.5
Maximum service tension: 4,516 kg
(= 11,290/2.5)

8.5.7 Support design

(1) Support strength

Steel towers are most commonly used as high voltage overhead transmission line supports because of the extremely high strength required. Steel towers shall be designed to withstand either one of the following, with a normal assumed load or two thirds of assumed load at the time of abnormality.

1) Normal assumed load

We will examine the situation where the vertical load and horizontal load are imposed at the same time, as wind pressure works at right angles to the electrical lines and in the same direction as the electric lines. We will nominate the greater wind directional condition load with stress on the steel tower components as the normal assumed load.

2) Assumed load during abnormality

We will nominate an assumed load during abnormality which considers scenarios in which the electrical wires are cut. The unbalanced tension resulting from the cut wires and the consequent torsion force are imposed on the normal assumed load. We will calculate the load for wind pressure working at right angles to the electrical line, and where the load is imposed in the same direction as the electrical line. We will adopt the greater stress on each component.

(2) Wind pressure load

The design wind velocity adopted for this project is 40 m/s. The wind pressure is based on this wind velocity and calculated as follows.

Theoretical wind pressure formula:

$$P = (\frac{1}{2}\rho V^2) \cdot c$$

Where, P: wind pressure (kg/m^2)

p: Air density (kg • s^2/m^4)

V: Wind velocity (m/s)

c: Air resistance coefficient (based on wind tunnel test)

The wind pressure on the electrical wires becomes P = 92 kg/m^2 if we insert $\rho = 0.115$, $V = 40$ and $c = 1$ in this formula. The wind pressure increases as the steel tower becomes taller, and is applied to the electrical wires at a uniform 100 kg/m^2. Based on the same calculation, the wind pressure applied to a steel tower is 290 kg/m^2. The wind pressure load is calculated by multiplying the wind pressure by the vertical projection area of the components.

(3) Structural design of the steel tower

An examination of component stress forms the basis of the structural design of the steel tower. Each joint of the frame materials is considered safe if the design stress calculated based on the assumed load is smaller than the strength of the structural materials (the angle steel and bolts). Given that the steel tower has a complex framework, a stress chart will be used as a simple means to calculate the tension and compressed force of each section. A stress chart expresses force using a vector and facilitates understanding on the distribution of external force in each section of the framework. The chart is commonly used in structural designing of steel towers.

(4) Steel tower clearance

1) Distance between the lines

It is important to avoid flashovers when electrical wires come in close proximity to each other because of horizontal sway caused by wind pressure, vibrations resulting from aeolian vibrations, or trembling in the lines. The following plan should be adopted to ensure that an appropriate distance is maintained between the lines:

(i) Horizontal distance: Ch (m)

Taking the example of a double circuit vertical array with a standard span, Ch is calculated using the following empirical formula. At a nominal voltage of 220 KV, Ch is between 8.2 m and 11.5 m.

$$Ch = 1.5 + V/(1.1\ k_1)$$

Where, V: Nominal voltage (KV)
k_1: Coefficient 20 - 30

(ii) Vertical distance: Cv (m)

The vertical distance is usually equivalent to 60 % to 100 % of the horizontal distance. The empirical formula that serves as the design guideline to set the standard span is as follows:

$$Cv = 1.0 + V/(1.1\ k_2)$$

Where, V: Nominal voltage (KV)
k_2: Coefficient 40 - 50

In the case of 220 KV, Cv = 5.0 - 6.0 m.

2) Line array and elevation

As the electrical lines are vertically arrayed, they require little horizontal space, and therefore offer excellent economy. Vertical arrays are the most common in arrays of two or more circuits, and will be employed in this project.

A wire elevation of 6 m is believed appropriate when the transmission voltage is below 160 KV. The elevation should increase by 12 cm for every additional 10 KV after 160 KV, so that the elevation for 220 KV should be 6.72 m. As the dip of the standard span is 9.5 m, when we add the length of long rod insulator, the elevation becomes 21.0 m. Given a sufficient design margin for geographical and meteorological conditions, we will choose an elevation where the principal component of the crossarm used to install insulator strings is 25.9 m from the ground.

This distance represents a standard design used for transmission line towers of this voltage.

Figure 8.5.3 shows a standard suspension steel tower shape and its clearance.

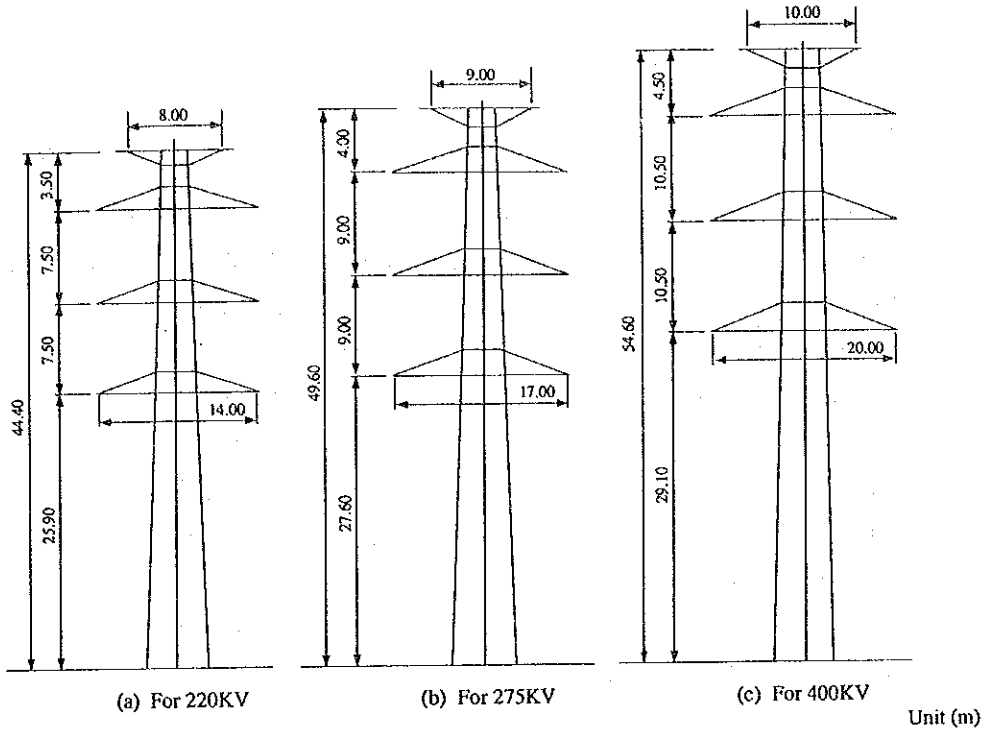


Figure 8.5.3 Standard Suspension Steel Tower

(5) Selection of the power line route

1) Selection process

The power transmission line route selected should facilitate future maintenance and construction, maintain supply reliability, respond to meteorological conditions and ensure economy. Specific selection procedures are as follows:

(i) Select a rough route that represents the shortest distance for the power lines by examining maps and taking local surveys using a helicopter.

(ii) Conduct an on-site survey of the rough route. Items that should be covered in the survey include topography, geology, meteorological conditions, household density, radiowave disturbance, natural conditions, landscape, road conditions, other electric wire facilities and ease of maintenance. This local survey should select the optimum route.

(iii) Survey the selected route. Surveys should include a central survey (distance between the center line of steel towers, horizontal angle and vertical angle), profile leveling (sectional leveling of the route), surveying of the site for the steel towers, and site surveying along the route and special places.

2) Planned route

The 220 KV power transmission lines for this project will be constructed along the mountains in parallel with the existing 132 KV power transmission lines with an approximate distance of 60 km between the Barka Power Station and the Madinat Qaboos Substation in the Muscat Power System. For the section between the existing Bait Barka Substation and the Musana Substation with an approximate distance of 52 km, the 132 KV power transmission lines are already constructed, suggesting that an interconnection with the Wadi Jizzi Power System is taken into consideration. A higher transmission voltage of 220 KV will be adopted when future interconnections with the Wadi Jizzi System and GCC countries are envisaged. In this case, the route of the 220 KV power transmission lines will be selected along the mountains in parallel with the existing 132 KV power transmission lines.

8.5.8 Aircraft Warning Sign

Based on the stipulations in OES 32, the following aircraft warning signs shall be employed:

(1) For night flights, a warning light operating on a dielectric current shall be attached to power lines across roads.

(2) As a sign for daytime flights, a sphere painted in orange (the aviation sign color) and made of aluminum or glass fiber shall be attached. The ball must be at least 600 mm in diameter and should be installed on overhead grounding wires.

(3) The steel tower shall be painted in orange (the aviation sign color) and white.

8.6 Substations

8.6.1 Bus System

(1) Type of bus system

The bus system has a particularly significant impact on substation reliability and economy. Following is a discussion of the kinds and characteristics of bus systems in common use at substations, which will be used as an index for selecting the system for the Barka Project.

1) Single bus system

The single bus system is simple, and hence economical. It is often used at small-scale substations.

2) Standard double bus system

This system uses a double bus and is equipped with a circuit breaker for bus connection. It requires more equipment and a larger area than the single bus system, but is easy to operate during normal operations and continues to operate during accidents or equipment and bus inspections.

3) Double bus 4 bus tie system

This system divides the standard double bus system into two sections, thereby enabling the scope of a power blackout to be locally contained following accidents in the bus. Consequently, the system is very flexible and is adopted for key substations in the trunk network.

4) 1 1/2 circuit breaker system

This system uses three circuit breaker units for two circuits. This has little effect on the system during bus accidents. This kind of system does not require the line to be shut down during circuit breaker inspection.

Figure 8.6.1 shows the structures of the four systems.

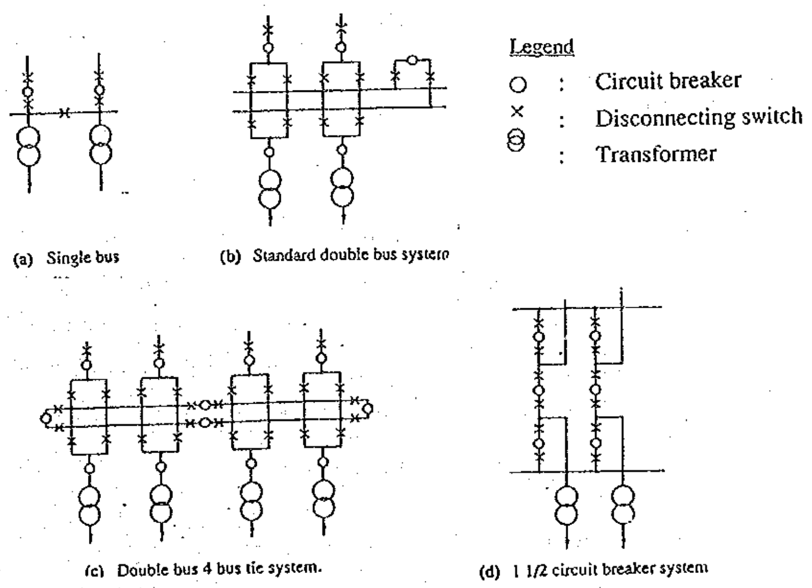


Figure 8.6.1 Bus Systems

(2) Selection of the bus system

The four types of bus systems shown in Figure 8.6.1 have been examined with selection guidelines of operationability during inspection and accidents, reliability and economy as well as ease of system operations. The examinations show the standard double bus system and double bus 4 bus tie system to be the most suited. Depending on the functions and the degree of importance of the substations under this project, the following bus systems will be selected:

1) As the Barka Substation to be built on the premises of the Barka Power Plant will have many circuits, we will adopt a double bus 4 bus tie system with a focus on system operations. The same system will also be employed at the existing Bait Barka and Madinat Qaboos Substations, taking into consideration system interconnection.

2) A standard double bus system will be used at other primary substations.

8.6.2 Lightning arrestor

(1) Basic functions

A lightning arrestor discharges when an abnormal voltage resulting from a lightning or a switching surge enters a power line. The arrestor reduces the peak value at the limited voltage or below and thereby prevents insulation breakdown and flashover in the insulators or equipment. The lightning arrestor must therefore have such self-restoring characteristics (follow current shut-down capacity) as shutting down discharged current automatically after restoring voltage.

(2) Rated voltage

The lightning arrestor must shut down follow currents at the rated voltage even when it is operated repeatedly in response to multiple lightning strokes. As the ratio (characteristic index) between the limited voltage and the rated voltage is virtually the same in any voltage class, the protection level of the lightning arrestor is determined automatically, based on the rated voltage. Determining the rated voltage is thus an important factor in designing the lightning arrestor.

The rated voltage for the lightning arrestor is expressed using the following formula:

$E_R = \alpha \beta Um = kUm$

Here, E_R: Rated voltage (KV)

α: Grounding coefficient

β: Tolerance

Um: Maximum allowable voltage (nominal voltage x 1.2/1.1) (KV)

k: $k = \alpha \cdot \beta = E_R/Um$ and is expressed as a percentage.

The grounding coefficient on the effective ground system is between 65 % and 80 %. We will adopt the 90 % lightning arrestor by adding 10 % tolerance to this value (namely $k = \alpha \beta = 0.9$). The rated voltage of the lightning arrestor for a 220 KV system is calculated as follows:

Maximum allowable voltage: Um = 220 x 1.2/1.1 = 240 KV (245 KV in accordance with IEC 71-1)

k% : 90 %

Rated voltage: 240 KV x 90% = 216 KV

(3) Characteristics

The insulation strength of the equipment includes lightning impulse withstand insulation level (LIWL) and switching impulse withstand insulation level (SIWL), depending on the system voltage. The protection level (limited voltage) of the lightning arrestor must be selected with tolerance incorporated in the equipment insulation strength.

Based on the above index, the lightning arrestor applied to the 220 KV system will have the following characteristics:

Nominal voltage:	220 KV
LIWI:	1,050 KV
Rated voltage:	216 KV
Limited voltage:	691 KV
Tolerance:	34 % ((1,050 - 691)/1,050 = 0.34)

(4) Installation position of the lightning arrestor

When the distance between the lightning arrestor and equipment to be protected (chiefly the transformer) is long, the value of the lightning surge voltage imposed on the equipment to be protected is higher compared to the limited voltage to the lightning arrestor. The difference grows larger as the distance increases, so the lightning arrestor should be set up as close to the equipment to be protected as possible (within 50 meters).

8.6.3 Main Transformers

(1) Type of transformers

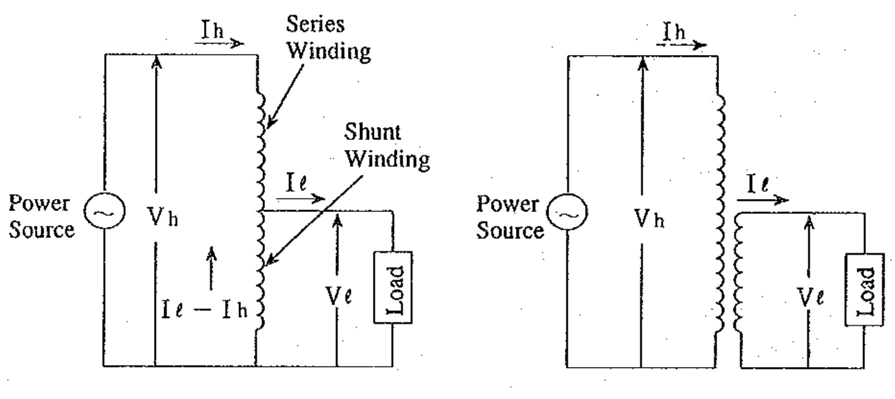
Transformers of Y - Y - Δ connection are often used at substations for power transmission. However, in systems where the primary and secondary sides use neutral direct grounding systems, it is possible to use an auto-transformer for Y - Y winding. The auto-transformer is not only very reliable but also offers excellent economy. In this project, 220 KV/132 KV main transformers will use an auto-transformer.

(2) Auto-transformer

Figure 8.6.2 shows a comparison of the connections between the auto-transformer and the two winding transformer.

The rating of the auto-transformer is equivalent to the two winding transformer which uses shunt winding and series winding. The following formula expresses the ratio of self capacity and line capacity in the form of a co-ratio.

Co-ratio α = self capacity/line capacity = 1 - Vl/Vh = 1 - Ih/Il



(a) Auto-transformer (b) Two Winding Transformer

Figure 8.6.2 Connection of Transformers

When Vh:Vl approaches 1, α becomes small. This means that self-capacity, which is closer to real transformer capacity than line capacity, can be small. Furthermore, as the current (Il - Ih) of the shunt winding becomes small, the winding used in this section can be small. More specifically, if we insert Vh = 220 KV and Vl = 132 KV in the above formula, α becomes 0.4. When the same amount of power must be supplied to the load, the auto-transformer can suffice with 40 % self-capacity compared to the two winding transformer.

(3) Advantages and concerns of the auto-transformer

Auto-transformers are compact and light, and thereby ensuring greater economy. Furthermore, a smaller co-ratio minimizes iron and copper losses, giving greater efficiency. As percent impedance is lower, the voltage fluctuation rate is reduced and system stability improved.

When the percent impedance is too low, the short circuit current increases, causing problems in terms of the transformer's thermal and mechanical strength. The percent impedance widely used for the voltage level applicable under this project is about 14 % in terms of the line capacity standard. However, OES 27 stipulates that 18 % be used on the 132 KV system. Therefore, in designing transformers it is important to take into consideration the electromagnetic force during short circuits.

(4) Changing taps

To compensate for fluctuations in secondary voltage of the transformer as a result of fluctuations in the power source voltage and load and thereby maintain a uniform secondary voltage level, a tap changer shall be installed on the higher voltage side of the transformer.

One tap shall be 1.1 % and a total of 19 taps shall be installed (in accordance with OES 27) within the range of +5/-15 % against the rated voltage.

(5) Capacity of interconnected transformers

In relation to the current highest voltage of 132 KV, after selecting the higher optimum voltage, the capacity of the transformer that will link up to this voltage and the existing 132 KV shall be selected from among the standard unit capacities of 125 MVA, 200 MVA and 250 MVA, by meeting the following conditions:

1) The Bait Barka Substation shall have two banks and Madinat Qaboos Substation shall also have two.

2) When one bank of transformers is shut down during operations, this shall not cause an overload on other transformers.

3) Even when one power transmission line is shut down, this does not cause an overload on the transformer.

8.6.4 Switchgears

(1) Selection of type of switchgears

Along with the transformers, the switchgear is the most important equipment constituting the substation. The switchgears shall therefore be selected subsequent to the following examinations:

Under this project, the substations will be located in hot and humid places that expose them to damage from salt dust. In terms of insulation strength, the equipment at the substation will therefore encounter a very severe environment. The substation will also be located close to electricity consumers, so that the area for the substation site and its capacity will be limited. The switchgears selected must also ensure steady insulation strength, very little deterioration over time and greater labor economy in operations, maintenance and inspection.

The switchgears that meet these requirements is the SF_6 gas insulated switchgears (GIS). Circuit breaker, disconnecting switch, instrument transformer and bus are all incorporated in the metal enclosure, and the SF_6 gas (six sulfur fluoride) which excels in insulation capacity are filled. Furthermore, OES 27 stipulates the use of GIS for the 132 KV circuit. Consequently, GIS will be used for the 220 KV circuit in this project.

(2) GIS characteristics

The live part of GIS is not exposed at all. This ensures safety and avoids problems of damage or contamination. It also reduces insulation distance and therefore offers the key feature of taking up significantly less substation area and capacity. Compared to the conventional outdoor type substation, GIS requires 20 % area and 10 % volume, although this differs from one voltage class to another.

The SF_6 gas used as GIS's insulation and arc-suppression catalyst has high breakdown voltage and excellent arc-suppression characteristics. It has chemical stability, is non-toxic, has no odor and does not burn. It also has excellent thermal conductivity, giving it a significant cooling effect. SF_6 gas is inert and therefore minimizes the wear on the contact element of the circuit breaker because of arcs, reducing the frequency of inspection. SF_6 gas poses one concern. It is liquefied at a pressure of 12 kg/cm^2 g or above at a temperature of 0°C. However, the ambient temperature and pressure under this project are outside this range, so this will present no problems in actual application.

The most common shut down method employs a puffer system that carries out arc-suppression by spraying SF_6 gas compressed by the cylinder from the nozzle to the arc. The time constant of arc-suppression which serves as guideline for arc-suppression capacity is about 1/100th of air. Therefore, SF_6 gas has an arc-suppression capacity about 100 times greater than that of air.

8.6.5 Phase Modifying Equipment

(1) Role of phase modifying equipment

The system reactive power changes depending on the load and power flow of the system. When the reactive power is excessive, it increases the system voltage. On the other hand, when the reactive power is low, it causes a drop in the system voltage. The phase modifying equipment are designed to counter power loss and maintain system voltage. The phase modifying equipment are installed in a decentralized manner at places where shortages in system reactive power are encountered.

(2) Type of phase modifying equipment

The static capacitor and shunt reactor are economical for use as phase modifying equipment. They enjoy widespread application because they facilitate maintenance. When their unit capacity is greater, construction costs are low. However, they must be selected so that voltage fluctuations at the time of switching on and off and opening do not exceed 2 %. The kinds and applications of phase modifying equipment are given below.

1) Static capacitor

The static capacitor is used to improve the system's lagging power factor and compensate for voltage drops. It is installed in places where the system's reactive power runs short. It is normally connected to the secondary bus of the primary substation in combination with a switching device. Static capacitor quantity is controlled by making the switching device on and off. Static capacitor quantity is therefore controlled in stages. This will not cause any problems in actual use. It is characterized by a small power loss, easy operations and maintenance and low construction costs.

2) Shunt reactor

Unlike the static capacitor, the shunt reactor compensates for the system's leading reactive power and controls the increase in voltage. On a system where cables are frequently used for power transmission and distribution lines, the shunt reactor is used to compensate for the leading current of the cable and prevent increases in system voltage.

3) Static var compensator (SVC)

This combines a static capacitor and a shunt reactor controlled by the thyristor. It enables continuous adjustment of leading and lagging reactive power.

This project predicts a shortage in system reactive power. Consequently, a static capacitor will be used. Facility capacity and unit capacity (control quantity) will be selected based on system analysis. In accordance with OES 30, the single capacity of the static capacitor is 1 MVA and is connected to the 11 KV bus.

8.7 Load Dispatching System

8.7.1 Need for an automatic loading dispatching system

When the Barka Power Plant begins operations in phases, in response to increases in electricity demand, the facilities and systems constituting the power transmission lines, substations and other facilities comprising the power supply system will become larger in scale and more complex. In addition, if the Wadi Jizzi system and Manah system are interconnected to the Muscat system in the near future, a comprehensive and organic interconnection will be necessary. This means that it will be very difficult to manually control power flow, adjust system frequencies, optimize system voltage and other system control operations, understand the system status as it changes from time to time or monitor the operations status at one load dispatching center. It would also be hard to assess the situation when accidents are encountered within the system and to carry out rapid and smooth recovery operations. It will therefore be vital to build and operate an automatic load dispatching system in conjunction with a shift to greater mechanization and automation of the facilities that make up the power system.

At present, MEW gives the Ghubrah Power Plant the functions of a load dispatching center and has installed communications terminals at the Rusail Power Plant and seven primary substations. Thus, MEW carries out power supply operations using a power line carrier network. Information exchanged between power plants and substations on a daily basis primarily include measurement of power flow and monitoring and reporting. As the operations depend on human operators, there is significant scope for automation.

8.7.2 Load Dispatching Operations and System Information

Load dispatching should rationally and economically operate the power supply facilities to ensure a continuous supply of quality power to consumers. Achieving this goal requires that load dispatching operations form the core of power station operations. These load dispatching operations must include frequency, voltage and power adjustment as well as operation and shut down of power generation and substation facilities and recovery operations in the wake of accidents.

Table 8.7.1 shows the controls and operations conducted by the load dispatching center. The power station collects system information from the power system.

Table 8.7.1 Load Dispatching Operation and System Information

	Control and operation	System information	Monitoring items	Calculation, judgment and determination	Connection to the purpose of load dispatching operation
Monitoring Demand & Supply	Frequency control, economic load dispatching control (including load forecast control).	Frequency Interconnected power and generated power (KWh) Power plant output Meteorological conditions.	Frequency Interconnected power deviation and power (KWh) deviation Difference between total demand and forecast demand, Reserve capacity	Required adjustment quantity (current and forecast point) Output allocation Load band revision of each power plant Generator start up and shut down Revision of demand forecast, and output forecast Revision of power generation schedule	Maintenance of supply and demand balance Maintenance of regulated frequencies Economical output allocation of power plants
Monitoring Voltage	Voltage and reactive power control	Voltage Reactive power flow OLTC tap Phase-modifying equipment operating conditions.	Voltage deviation Reactive power flow deviation Fine tuning of power and reactive power adjustment equipment. Excess capacity	Required adjustment quantity.	Maintenance of regulated voltage Appropriate allocation of reactive power.
Monitoring Reliability	System operation during normal use (including control to prevent the effects of accidents) System operations during accidents	System structure condition (switching of circuit breaker and disconnecting switch). Power flow Power plant output Frequency Interconnected power Voltage Meteorological conditions	Power flow bottleneck Operation reserve capacity Effect of assumed accidents Accident detection (relay operations and abnormal changes in frequency and interconnected line power flow) Accident conditions (such as places where accidents are encountered, scope, type and problems in power supply interruption)	Method to eliminate flow bottlenecks. (Such as revisions to the system configuration or transfer of power plant output). Preliminary measures to localize accidents (such as revising system configuration, transferring power plant output or suspending operations). Methods to recover from accidents (such as revising system configuration, mobilizing operations reserve capacity, or power source and load shut down and system separation).	• Appropriate measures against changes in normal system status which are forecast to develop into accidents. Appropriate preliminary measures against anticipated accidents. Quick and appropriate recovery measures following accidents.

8.7.3 Automation Load Dispatching System

The automatic load dispatching system comprises the basic functions shown in Table 8.7.2.

Table 8.7.2 Basic Functions of Automatic Load Dispatching System

Automatic load dispatching	Operation plans	(1) Next day's supply and demand plan: load forecast, determination of parallel generators, economic operation plans and operational reserve capacity allocation, etc. (2) Reactive power supply plan: operation reference voltage calculation. (3) Scheduled shut down plan: forecast calculation of voltage and current.
	System control	(1) Frequency and real power control: frequency control and economic load dispatching control, load forecast control, power flow control. (2) Voltage and reactive power control.
	System operations	(1) Normal operations: revision to demand conditions and operations following operation shut down plan. (2) Operations during accidents: measures to avert frequency drop, overload and supply problems, and automatic operations of recovery from accidents.
	Status monitoring and recording	(1) Monitoring of system conditions: frequency, voltage, power line and transformer power flow, circuit breaker switching conditions, operational reserve capacity quantity and other system supply reliability. (2) Collection of operation records.
	Operation evaluation	(1) Power generation and load statistics. (2) Examination and evaluation of operation results.

Among the basic automatic load dispatching system functions, system control and status monitoring require quick response characteristics. These functions must therefore be processed by computer. However, except where the operations are simple, computers are not well suited to operations to recover from accidents. Such operations shall be left up to experienced operators for the present.

As shown in Table 8.7.1, system information transmitted from the power plant and substation to encourage automation is diverse and large in volume. The transmission quantity and speed by the power line carrier facilities which MEW currently uses may not be sufficient. If so, the existing system will have to be replaced with a microwave radio or fiber-optic complex overhead grounding wire (OPGW) as the power communications method.

8.7.4 Central Load Dispatching Center

Because it is the core of load dispatching operations, a central load dispatching center may be set up in the Barka Power Plant, giving consideration to the position of the facilities of the Muscat and Wadi Jizzi systems in the future and load distribution status. However, taking into consideration the fact that power supply facilities are located close to the load centers and security must be given high priority, we plan to set up a central load dispatching center at the Ghubrah Power Plant.

CHAPTER 9 CONCEPTUAL DESIGN OF DESALINATION PLANT

CHAPTER 9 CONCEPTUAL DESIGN OF DESALINATION PLANT

9.1 Design Criteria, Standards

The basic design conditions for the planning of the desalination plant are described as the followings:

9.1.1 The Quality of the Sea Water and Sea Bottom Soil

The results of the analyses of the sea water and the sea bottom soil obtained off the coast of Barka Site during the 1985 Feasibility Study and for this study are given in Annex 9.1. A comparison of the results and the Tender Conditions of the Ghubrah Desalination Plant has resulted in the raw sea water to be used for the conceptual design conditions for this project and is given in Table 9.1.2.

9.1.2 The Raw Sea Water Temperature

In determining the design sea water temperature, the actual sea water temperature must be obtained at the intake water point where the draft is shallow especially like the Barka Site. The year round sea water temperature at Ghubrah Power Station taken for the 1985 Feasibility Study was used as a reference, and the following temperature was established for the design:

Design Condition	30°C
Maximum Allowable Temperature	35°C

9.1.3 Product Water Quality

The standard quality of drinking water in the Sultanate of Oman is described in the Omanian Standard No. 8 Drinking Water. The standard is given in Table 9.1.3.

The product water quality for this project will conform to the standard values.

9.1.4 Electricity and Steam

(1) Electricity

The electric power required for the operation of the desalination plant will be supplied from the electric power plant in this project. The supply conditions are shown in Table 9.1.1.

Table 9.1.1 Supply Conditions of Electricity

Item	Supply Condition
Frequency Phase	50 Hz 3 Phase

Table 9.1.2 Quality of Raw Sea Water

Item	Unit	Value
Turbidity	-	0.5 ~ 1.4
pH	-	7.9 ~ 8.1
Electric Conductivity	ms/cm	56.0
Acid Consumption (Alkalinity)	$mgCaCO_3/l$	120
Total Hardness	$mgCaCO_3/l$	6,750
Suspended Matter (SS)	mg/l	0.7
TDS (110°C)	mg/l	39,500
COD_{MN}	mg/l	0.9
COD_{OH}	mg/l	0.2
TOC	mg/l	0.8
Cl	mg/l	21,500
SO_4	mg/l	2,940
T-N	mg/l	≦ 0.5
Si ad SiO_2	mg/l	0.17 ~ 0.54
Ca	mg/l	460
Mg	mg/l	1,440

(2) Steam

All quantities of steam required for the MSF plant will be supplied from the electric power plant.

9.1.5 Other Matters to be Considered for the Desalination Plant

In order to make the operation and maintenance of desalination process of the plant easy, while keeping a high working efficiency, the following matters will be considered:

(1) Automatic control system will be used for the operation of the desalination plant including start-up and shutdown, and this will be performed from the central control room.

(2) All rotating equipment, with the exception of the brine re-circulating pump, will be provided with a standby pump for this project.

Table 9.1.3 Omanian Standard No. 8 Drinking Water (OS8/1978)

Item	Unit	Condition
1) Physical Properties		In General
Color		Colorless
Taste & Odour		Tasteless & Odourless
Turbidity		Free
2) Chemical Properties		
a. Toxic chemicals		Maximum Permissible Level
Lead	mg/l	0.10
Selenium	mg/l	0.01
Arsenci	mg/l	0.05
Cadmium	mg/l	0.01
Cyanide	mg/l	0.05
Mercury	mg/l	0.001
b. Chemicals that have special effects on health		
Fluoride	mg/l	0.8
Nitrate	mg/l	45
3) Bacteriological Properties		
a. Treated water		
Escherichia Coliform	number/ 100 ml	0
Coliform Organisms	number/ 100 ml	10
Throughout any year, 95 % of the samples examined should not contain any coliform organisms in 100 ml.		
b. Untreated water		
Escherichia Coliform	number/ 100 ml	0
Coliform Organisms	number/ 100 ml	10

Table 9.1.3 Omanian Standard No. 8 Drinking Water (OS8/1978) (Continued)

Item	Unit	Level	
		Highest Desirable Level	Maximum Permissible Level
c. Chemicals that effect the suitability of water			
Total Dissolved Solids	mg/*l*	500	1,500
Copper	mg/*l*	0.05	1.5
Iron	mg/*l*	0.1	1.0
Magnesium	mg/*l*	Not more than 30 mg/*l* if there are 250 mg/*l* of sulphate. If there is less sulphate, magnesium up to 150 mg/*l* may be allowed.	150
Manganese	mg/*l*	0.05	0.5
Zinc	mg/*l*	5.0	15
Calcium	mg/*l*	75	200
Chloride	mg/*l*	200	600
Sulphate	mg/*l*	200	400
Phenolic Compounds (as phenols)	mg/*l*	0.001	0.002
Total Hardness	mg/*l*	100	500
pH Range	-	7.0 ~ 8.5	6.5 ~ 9.0
		Level	
d. Minimum residual chlorine concentrations	mg/*l*	0.2 ~ 0.5	

9.2 Desalination System

9.2.1 Comparable Desalination Processes

Although there are various desalination processes, the Multi-Stage Flushing (MSF) process shares 71.7 % and the Reverse-Osmosis (RO) process shares 19.4 %, so their total share exceeds 91 %, as shown in Figure 9.2.1, among large desalination plants of 4,000 m^3/d or more capacity, as of the end of 1993.

In our evaluation, therefore, it is focused to compare both, MSF and RO processes, together with economical aspect in order to select an optimal one from them for this project.

9.2.2 Inventory Records for Desalination Plants

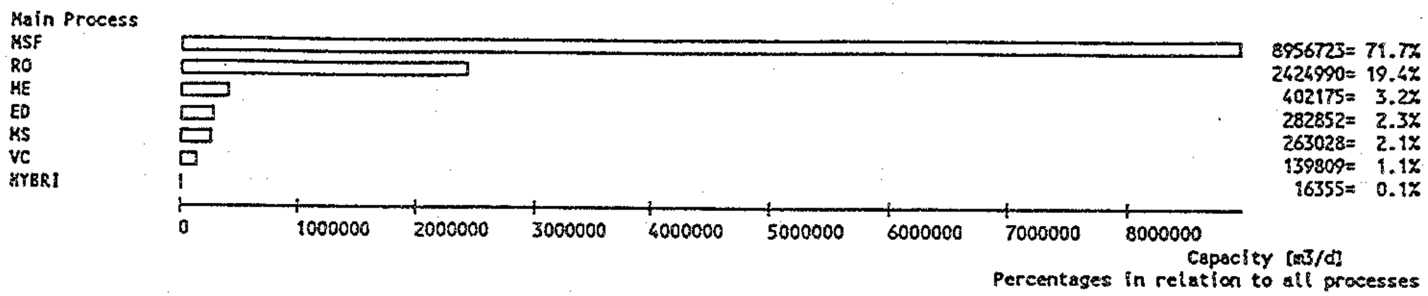
The foregoing data are given for present share of existing desalination plants. Comparing these data to the past ones as of the end of 1991, it is understood that RO process increases 1.6 point from 17.8 % while MSF process decreased reversely 1.6 point from 73.3 %. It is the fact the RO process plants steadily increases the share, year after year.

The reason of later application of RO process for sea water desalination is explained as the initiation was for brackish water with small scale. However, it is now making rapid progress in its share with high reliability in RO process through technical improvement for large scale sea water desalination plant.

Recent orders for large scale sea water desalination plants of 4000 m^3/d and more capacity are shown in Table 9.2.1 and Table 9.2.2, referring to the statistical data of International Desalination Association (IDA)Inventory. Also, from the data in Table 9.3.3 shown as classified for each process, it can be seen RO process share of 16 % in sea water desalination, for the research period, 1990 to 1993. In Table 9.2.4, RO process plants 4,000 m^3/d or more in capacity for sea water desalination are shown, of both operating and ordered ones.

9.2.3 Reliability of MSF and RO processes

The MSF process established around 1960 is matured and stable in technology, unlikely to advance in the principle etc. from now.



CAPACITY of all land-base desalting plants capable of producing 4,000 (m^3/d)/UNIT or more fresh water vs. PROCESS

MSF	:	multi stage flash
RO	:	reverse osmosis
ME	:	multi effect evaporation
ED	:	electrodialysis
MS	:	membrane softening
VC	:	vapour compression
HYBRI	:	hybrid process

Note: An except from "Desalting Plants Inventory Report No. 3", April 1994 by International Desalination Association (IDA).

Figure 9.2.1 Inventory Records of Desalination Plants

Table 9.2.1 Sea water Desalting Plant rated 4,000 (m^3/d) or more and constructed in 1990 and 1991

No	Country	Location	Capac. m3/d	Unit	Process	Equip	Feature	Customer	User	Cn Year	Op Year	Manufacturer	Additional Information
1	USSR	Tobolsk	15,600	1	ME	VTE			MUNI	90	92	USSR SU	
2	Virgin Islands	St. Croix	4,921	1	ME	HTE	HST	VIALCO	INDU	90	91	IDE IL	
3	Virgin Islands	St. Croix	4,921	1	ME	HTE	HST	HESS OIL	INDU	90	91	IDE IL	
4	Virgin Islands	St. Thomas	5,299	1	ME	HTE	HST	VIWAPA	MUNI	90	92	IDE IL	
5	Arab Emirat. UAE	Dubai Jebel	272,760	8	MSF	Flash		DUBAI ELECTRIC	MUNI	91	93	WEIRWESTGARTHGB	MC:SIEMENS D
6	Arab Emirat. UAE	Taweelah B	3,500	1	MSF	Flash	HST	WED	MUNI	91	94	SIDEM F	Unit No.4
7	Neth. Antil. NA	Aruba	6,056	1	MSF	Flash	HST	Water & Power	MUNI	90	92	AQUA CHEM USA	
8	Oman OMA	Ghubrah 5	27,240	1	MSF	Flash	HST	MEW	MUNI	90	92	HITACHI ZOSEN	MC:ABB CH
9	Qatar Q	Abu Fontas	45,540	2	MSF	Flash		MEW	MUNI	90	92	FTC I	DP 270 MW GAS
10	Saudi Arabia SA	Medina/Yanbu	144,000	4	MSF	Flash		SWCC	MUNI	90	94	SNAM PROGETTI I	MC:BELLELI
11	Egypt ET	Hurgadah	5,000	1	RO	SWM			MUNI	90	90	ISEL CDN	
12	Great Britain GB		15,925	3	RO	MTU		AGIP TIFFANY	INDU	91	92	WEIRWESTGARTHGB	Sulphte Removal
13	Italy I	Sicily	18,000	4	RO	HFM			MUNI	91	92	SNAM PROGETTI I	
14	Malta M	Pembroke	26,930	5	RO	HFM	ER	Republic MDI	MUNI	90	91	POLYMETRICS USA	
15	Neth. Antil. NA		4,542	1	RO	MTU		GEBE	MUNI	90	91	AQUA DESIGN USA	BOOT
16	Saudi Arabia SA	Jeddah V	56,800	10	RO	MTU		SWCC	MUNI	91	94	MITUBISHI J	Rehab Phase II
17	Spain E	Cl Aguimas	10,000	2	RO	SWM		Municipality	MUNI	91	93	PRIDESA/PASA E	
18	Spain E	Cl Del Rosar	4,000	1	RO	MTU		Municipality	MUNI	91	92	FOMENTO OBARS E	
19	Spain E	Cl Gran Cana	10,000	2	RO	HFM	ER	AGRAGUA	IRR	90	91	CADAGUA E	
20			97,000	2	RO	SWM			INDU	90	91		
21	Arab Emirat. UAE	Jebel Dhanna	4,540	1	VC	HTE	TVC	WED	MUNI	90	91	SIDEM F	
22	Arab Emirat. UAE	Mirta	9,080	2	VC	HTE	TVC	WED	MUNI	90	91	SIDEM F	
23	Arab Emirat. UAE	Sila	4,540	1	VC	HTE	TVC	WED	MUNI	90	91	SIDEM F	
24	Italy I	Sicily	18,000	2	VC	HTE	TVC	Reggione Sicili	MUNI	90	93	SIDEM F	MC:TPL I
25	Italy I	Sicily	18,000	2	VC	HTE	TVC	Reggione Sicili	MUNI	90	93	SIDEM F	MC:TPL I
26	Italy I	Sicily	18,000	2	VC	HTE	TVC	Reggione Sicili	MUNI	90	93	SIDEM F	MC:TPL I

Table 9.2.2 Sea water Desalting Plant rated 4,000 (m^3/d) or more and constructed in 1992 and 1993

No	Country	Location	Capac. m^3/d	Unit	Process	Equip	Feature	Customer	User	Cn Year	Op Year	Manufacturer	Additional Information
1	Arab Emirat. UAE	Mirfa	73,800	3	MSF	Flash	HST	WED	MUNI	93	96	ANSALDO I	DP 200MW
2	Arab Emirat. UAE	Ruwais	14,500	1	MSF	Flash		Ruwais Refinery	INDU	93	95	HITACHI ZOSEN J	
3	Arab Emirat. UAE	Taweelah B	345,600	6	MSF	Flash		WED	MUNI	92	95	ITALIMPINTI I	MCO:TRACTEBEL B
4	Egypt ET	Hurghada	4,996	1	RO	SWM	ER	SCIENT TRADING	TOUR	92	94	AES USA	BOOT
5	Iran IR	Queshm Island	120,000	4	MSF	Flash			MUNI	92	95		DP 250MW
6	Kuwait KT	Az Zour South	109,000	4	MSF	Flash		MEW	MUNI	93	96	MHI/SASAKURA J	
7	Libya LAR	Mlita	20,000	2	MSF	Flash	HST	GEC	MUNI	93	95	HYUNDAI SKO	DP 1360MW
8	Libya LAR	Ras Lanuf	8,400	1	MSF	Flash	HST	RASCO	MUNI	93	95	ANSALDO I	
9	Libya LAR	Sirte	20,000	1	MSF	Flash	HST	GEC	INDU	93	95	HYUNDAI SKO	
10	Malta M	Pembroke	8,800	2	RO	HFM	ER	Government	MUNI	93	93	POLYMETRICS USA	
11	Malta M	Pembroke	27,600	6	RO	HFM	ER	Government	MUNI	93	94	POLYMETRICS USA	
12	Neth. Antil. NA	Aruba San Nicol	6,000	1	VC	HTE	TVC	COASTAL ARUBA	INDU	92	93	IDE IL	BOOT
13	Neth. Antil. NA	Curacao	6,000	1	MSF	Flash	HST	Isla Refinery	INDU	93	95	SIDEM F	
14	Qatar Q	Abu Fontas B	150,000	5	MSF	Flash	HST	QEWC	MUNI	93	97	WEIRWESTGARTHGB	DP 600MW
15	Qatar Q	Dukhan	9,160	2	VC	HTE	TVC	QGPC	INDU	92	94	SIDEM F	
16	Saudi Arabia SA	Al Jobail	108,000	10	RO	MTU		SWCC	MUNI	93	95	PREUSSAGNOELL D	
17	Saudi Arabia SA	Al Khobar III	280,000	8	MSF	Flash	HST	SWCC	MUNI	93	97	HITACHI ZOSEN J	
18	Saudi Arabia SA	Medina/Yanbu II	128,000	15	RO	HFM		SWCC	MUNI	92	95	MITSUBISHI J	MCO:KULJIAN USA
19	Saudi Arabia SA	Shuaiba I	454,000	10	MSF	Flash		SWCC	MUNI	93	96	KHI SKO	
20	Saudi Arabia SA	Yanbu	27,400	2	MSF	Flash		ROYAL COMMISSIO	INDU	93	96	MITSUI J	
21	Singapore SGP	Pulau Bukom	4,500	1	VC	HTE	TVC	SHELL	INDU	93	94	SIDEM F	
22	Spain E	CI Arucas-Moya	4,000	1	RO	SWM		Municipalty	MUNI	93	94	PRIDESA/PASA E	
23	Virgin Islands	St. Croix	5,000	1	VC	HTE	TVC	VIWAPA	MUNI	92	93	IDE IL	
24	Virgin Islands	St. Croix	4,921	1	VC	HTE	TVC	VIWAPA	MUNI	92	93	IDE IL	
25	Virgin Islands	St. Croix	4,921	1	VC	HTE	TVC	HESS OIL	INDU	93	95	IDE IL	

Table 9.2.3 Sea water Desalting Plant rated 4,000 (m^3/d) or more and constructed in 1990 and 1993

Process		Number of Plant	Total Capacity	Share	Number of Unit	Capacity of Unit
			m3/D	%		m3/D/Unit
Multiple Effect Distillation	ME	4	30,741	1.1	4	7,685
Multi Stage Flash Evaporation	MSF	19	2,159,296	78.8	65	33,220
Reversa Osmosis	RO	16	442,293	16.1	66	6,701
Vapor Compression	VC	12	106,662	3.9	17	6,274
Sum			2,738,992	100.0		

Table 9.2.4 Sea Water Desalting Plant with RO

Country	Location	Capac. m^3/d	Unit	Customer	User	Cn Year	Op Year	Manufacturer	Membrane Manufacturer
Saudi Arabia SA	Dhahran	4,000	1		INDU	82	83	ENVIROGENICUSA	ENVIROGENICUSA
Bahrain BRN	Ras Abu Jarjur	46,000	7	MEW	MUNI	82	84	SC/SAKURA J	DUPONT USA
Saudi Arabia SA	Umm Lujj	4,400	1	SWCC	MUNI	82	85	FLUID SYST. USA	FLUID SYST. USA
Malta M	Ghar Lapsi	4,000	1	Government	MUNI	85	86	POLYMETRICS USA	DUPONT USA
Malta M	Tingne	5,000	1	Government	MUNI	86	87	POLYMETRICS USA	
Arab Emirat UAE	Bani Yas	4,600	1	WED	MUNI	85	88	IRITECNA I	DUPONT USA
Arab Emirat UAE	Dalma	9,200	2	WED	MUNI	85	88	IRITECNA I	DUPONT USA
Malta M	Tingne	5,400	1	Government	MUNI	87	88	POLYMETRICS USA	
Saudi Arabia SA	Jeddah	56,800	10	SWCC	MUNI	86	88	MITSUBISHI J	TOYOBO J
Spain E	Cl Gran Canaria	4,000	1	JULIANO BONNY	IRR	87	88	FLUID SYST. USA	FLUID SYST. USA
Bahrain BRN	Al Dur	45,000	8	SWCC MEW	MUNI	64	89	WEIRWESTGARTHGB	DUPONT USA
Oman OMA	Sur	4,500	1	WED Abu Dhabi	MUNI	87	90	AQUA ENG. A	DUPONT USA
Spain E	Cl Lanzarote	5,000	1	Municipality	MUNI	89	90	PRIDESA/PASA E	FILMTEC USA
Spain E	Cl Lanzarote	5,000	1	Municipality	MUNI	89	90	PRIDESA/PASA E	FILMTEC USA
Spain E	Cl Las Palmas 3	12,000	2	EMALSA	MUNI	86	90	PRIDESA/PASA E	FILMTEC USA
Spain E	Cl Las Palmas 3	24,000	4	EMALSA	MUNI	86	90	PRIDESA/PASA E	FILMTEC USA
Malta M	Pembroke	26,930	5	Repubric HDI	MUNI	90	91	POLYMETRICS USA	
Neth Antil NA		4,542	1	GEBE	MUNI	90	91	AQUA DESIGN USA	
Spain E	Cl Gran Canaria	10,000	2	AGRAGUA	IRR	90	91	CADAGUA E	DUPONT USA
Great Britain GB		15,925	3	AGIP TIFFANY	INDU	91	92	WEIRWESTGARTHGB	DUPONT USA
Italy	Sicily	18,000	4		MUNI	91	92	SNAM PROGETTI I	DUPONT USA
Libiya LAR	Tripoli-West2	32,000	5	Municipality	MUNI	89	92	DVT D	
Spain E	Cl Del Rosario	4,000	1	Municipality	MUNI	91	92	FOMENTO OBRAS E	
Spain E	Cl Aquimas	10,000	2	Municipality	MUNI	91	93	PRIDESA/PASA E	
Saudi Arabia SA	Jeddah V	56,800	10	SWCC	MUNI	91	94	MITSUBISHI J	TOYOBO J
Egypt ET	Hurghada	4,996	1	SCIENT TRADING	TOUR	92	94	AES USA	FILMTEC USA
Malta M	Pembroke	8,800	2	Government	MUNI	93	93	POLYMETRICS USA	DUPONT USA
Malta M	Pembroke	27,600	6	Government	MUNI	93	94	POLYMETRICS USA	DUPONT USA
Saudi Arabia SA	Al Jobail	108,000	10	SWCC	MUNI	93	95	PREUSSAGNOELL D	DUPONT USA
Saudi Arabia SA	Medina/Yanbu II	128,000	15	SWCC	MUNI	92	95	MITSUBISHI J	TOYOBO J
Spain E	CI Arucas-Moya	4,000	1	Municipalty	MUNI	93	94	PRIDESA/PASA E	FILMTEC USA
Sum		698,493	111						

It may be got advantages economically through improving measures such as appropriate materials, plant scale merits and construction techniques, in conjunction with its high reliability. However, as this process issued in combination with power generation plants, it is often constrained in management of operation and maintenance.

The principle of the RO process was discovered by Sowirajan, Loeb et al. during the 1950s, and quickly progressed. However, it was adopted originally to desalinate brackish water, then applied to sea water typically as the first large RO process plant established in 1984 in Bahrain.

Early stage when RO process plants were introduced for sea water desalination, there were some troubles from abrupt degradation of performance. It has been made sure that caused by inadequate operation with membrane contacted by unneutralized chlorine (dosed for sterilization) as well as nature of membrane used of low chlorine resistivity. However, such troubles are now practically eliminated by means of improved membrane material and/or pre-treatment process, especially monitoring by ORP (Oxidation Reduction Potential) meter. Additionally, resulting of countermeasure to membrane surface contamination by suspended solids using appropriate sand filtration, frequency of the chemical cleaning could be reduced. Consequently, it is now ensured the guarantee service life by membrane supplier as 5 years normally, and recently 7 years guarantee also comes up to proposal.

Thus, in Saudi Arabia etc., there have been introduced with large scale RO process desalination plants. According to IDA statistical data, RO process plant with 4,000 m3/d and more capacity shares 16 % of total product water quantity as Table 9.2.3 among desalination plants contracted these 4 years from 1990 to 1993, as aforementioned. It is suggested that the reliability of RO process gets already practical for users, and also the evaluation of both processes may be enough in economy when the membrane exchange cost could be adequately assessed.

9.2.4 Technical comparison of MSF process and RO process

(1) Unit capacity

The MSF process meets generally large-capacity units for scale merit. Recently, unit capacities adopted in the Middle East are between 27,300 to 45,600 m^3/d (6-10 MGPD), and a concept of 54,700 m^3/d (12 MGPD) unit has been also examined. The largest plant ever built is the 900,000 m^3/d (5 MGPD/unit x 40 units) of Saudi Arabia's Al Jubayl Phase II Project.

Although the RO process has been mainly applied to small-scale units before, larger RO units have been constructed as mentioned in recent years. The largest plant ever built, including plants under construction, is Saudi Arabia's Medina-Yanbu Phase II Project, with a capacity of 128,000 m^3/d. There is provided one unit for the pre-treatment, then RO modules divided into 15 units with specific high pressure pumps. Also, each unit has a capacity of 8,480 m^3/d (1.87 MGPD).

(2) Energy consumption

The MSF process requires both electrical and steam energy, i.e., 3 - 4 KWh/m^3 of electricity and 120 - 175 kg/m^3 of steam. Oman has a plant with five MSF units, with a 6.0 design performance ratio. It takes higher energy consumption than the ratio of 8.0 to 9.0 generally designed in the most other same process plants.

The other hand, RO process only depends on electric power for itself, and has the minimum consumption among any process means. A large scale RO unit takes a power of 10 KWh/m^3, and will be able to reduce such consumption to 6 - 8 KWh/m^3 incorporating an energy recovery turbine.

Large scale MSF units are used as dual-purpose process for both electric power and steam supply, by which their energy efficiency can be significantly improved. For instance, a standard unit capacity of 31,800 m^3/d (7 MGPD) will export about 25 KWh/m^3 of electric power to outside.

Countries in the Middle East, such as Oman, are inevitable to drastic electric load fluctuation for seasonal weather condition, therefore, the RO process unit contributes to improve this load condition and availability of power generation plants due its to small but stable electric power demand even when the others demand more variation.

(3) Product water quality and post-treatment

Product water by MSF process has a quality close to pure water, with 25 ppm maximum TDS (Total Dissolved Solids). However, it is not palatable in drinking use due to such low hardness, and required to adjust the quality with post-treatment of the product water.

Product water by RO process meets drinking purposes, as is with 250 - 1,000 ppm TDS. However, its pH is slightly lower than the appropriate level, and required adjustment.

Additionally, bactericide sterilization is necessary in both cases, as well as further water quality adjustment is required to prevent corrosion in the water pipelines. These quality adjustment is performed by post-treatment in the manner of MSF process using carbon dioxide absorption and limestone bed filtration, while RO process by means of slaked lime dosing.

(4) Sea water intake quantity and quality

The MSF process needs a large quantity of water for cooling purpose, to intake 11 times the product water, and to discharge 10 times the product water. It means the recovery ratio of 11.

The RO process takes a smaller quantity of sea water than the MSF process, with the recovery ratio of 2.5. For RO process, as about 60 % of the drawn water is to be discharged, cost of water intake facilities significantly lower than about 90 % for the MSF process.

MSF process thermal efficiency increases when there is a large temperature difference between sea water going through the brine heater and brine in the final stage. That is to say MSF process thermal efficiency improves when the raw sea water is low temperature.

RO process in a condition (not exceeding a critical temperature to maintain the performance of membrane module) increases product water as close as to the allowable maximum limit by raw sea water temperature.

In case MSF process, it is preferable for the water to be free of volatile contaminants, such as phenol and ammonia, which may be dissolved again into water during distillation. However, the MSF process is not so significantly affected by the other factors. Scaling can be controlled by injecting a scale inhibitor. Deaeration is also required to sterilize the water and prevent corrosion.

For RO process, the quality of raw sea water affects the efficiency of pre-treatment, and is closely related to the membrane degradation. Raw sea water should be, therefore, as clear and low turbidity as possible. Generally, it is required higher quality control to RO process than to MSF, by means of pre-treatment for the sea water supplying to membrane module, including pH adjustment and elimination of suspending solids(SS). Poor elimination of SS such as silt causes deposition on the membrane and increases pressure loss. Poor sterilization results biological growth adhering to the membrane, causing choke and reducing membrane quality. Poor pH adjustment causes scale adherence to membrane, as well.

At present, however, these problems have been already eliminated with countermeasure technically, to ensure stable RO process operation.

(5) Management for operation and maintenance

a. Operation (start up and shut down)

To start up and shut down of MSF plant, it is required particular degree of operational skill. While the normal plant operation is automated, and the primary duty during watch is to monitor the instruments. MSF plant is normally inspected once per year, with plant shut down for about one month. The inspection includes maintenance works such as checking corrosion of the heat transfer tubes and evaporators, and calibration of instruments. Auxiliary MSF boilers need to be also inspected at the same time (if exist). The annual availability of a MSF plant is recently 85 to 90 %. A RO plant employs automatic start up and shut down operation, and the normal operation requires generally monitoring instruments. However, operating and maintaining the pre-treatment facilities of raw sea water are rather complex, requiring higher technologies.

b. Operation and maintenance personnel

MSF plants are usually operated with power generation plants and therefore require a relatively large number of operators. Staffs are also needed to maintain the boilers and turbines.

As RO plants have not direct complexity with power generation, they only require operators to control mainly the pre-treatment. Maintenance work can be conducted during operations. Required number of personnel to operate and maintain a RO plant is about 1/2 - 1/4 that required in a dual-purpose MSF plant.

c. Chemicals in use

The MSF process requires only small quantities of a few chemicals, mainly scale inhibitors and anti-foam agents.

The RO process requires such chemicals as coagulant, acid for pH adjustments and deoxidizing agents in the pre-treatment, and each of them with relatively large quantity. This process also requires occasional use of coagulants for back wash water treatment, and a chemical cleaning reagent for the RO module. In some cases, additionally, depending on the material of membrane used, a membrane regenerating agent to recover membrane performance (salt rejection rate) may be necessary, which results to make maintenance more complex for such treatment.

d. Maintenance and management

On maintenance schedule of MSF plant, it may be often constrained tightly from power generation plant due to annual inspection etc., because the power plant is incorporated with MSF plant to reduce steam generation cost by means of electric power generation.

In case of RO plant, it has no relation direct to such power station so that the plant operation and maintenance may be independently managed. Further, it is ensured the plant availability with redundant installation for such as pumps, considering safety operation. There are also applied with segmental (8 - 10) divisions at high pressure body to facilitate partial inspection during operation. Availability of RO process plant is, therefore, expected up to 90 - 95 % and the plant management is very easy. For replacement or cleaning of the membrane element, it can be conducted enough with partial plant shut-down.

(6) Construction

a. Space requirement

A RO plant generally requires a smaller space. Figure 9.2.2 is a plot plan for MSF and RO plants with a capacity of 27,360 m^3/d (6 MGPD), where is shown layout of a RO plant about 12 % less space than that of a MSF plant.

b. Construction period

A MSF plant requires a 30-month construction period after conclusion of contract, while a RO plant requires about 24 months. Both periods will depend finally on the construction period for the power plant.

In this Barka Power Generation and Desalination Plant Project, the target of completion for the First Stage is set in 1998, so the time allows only about two years for net construction period considering four years more and less remaining in total starting from the budgeting to the contract. While it has some disadvantage for MSF plant which will be taken 2.5 years until completion, RO plant is expected to fit the required construction period, in combination with gas turbine plant which is quickly deliverable, if on-site work condition such as power supply would be timely provided.

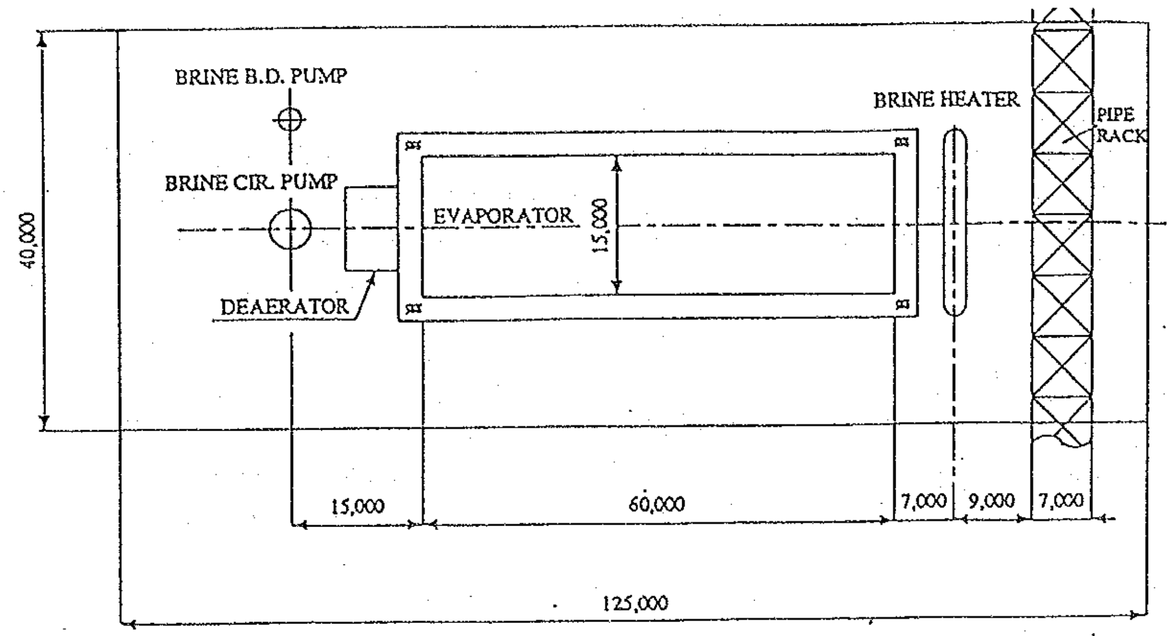
(7) Environmental impact

There are some factors which affect surroundings such as discharge water, noise, and exhaust gas (especially for MSF plant). For discharge of brine, MSF process effluents warm brine while RO process does considerably high concentrated one. However, it is believed either of them gives a minimal impact to the surroundings.

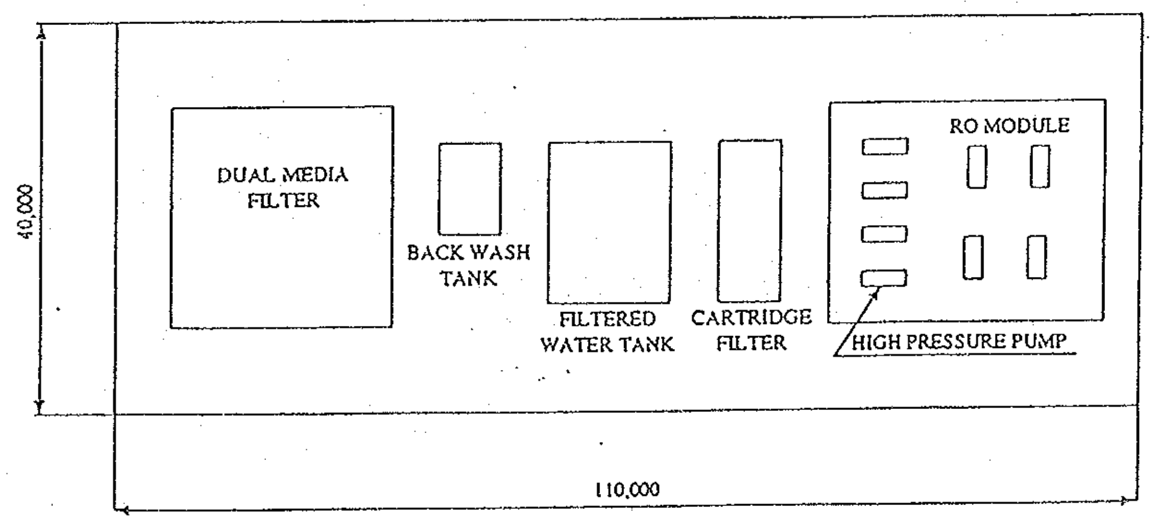
For noise, it can be reduced to an acceptable level for both process plant by careful layout and appropriate noise abatement.

Although MSF plants exhaust gas from the steam generator(boiler), they use natural gas as the fuel, and do not cause any air pollution through sulfuric oxide or soot.

Thus, neither type of plant has significant impacts on surroundings. However, the issue of CO_2 regulation, which did not exist at the time of the 1985 feasibility study, has gained prominence with concerns over global warming trends. Specific CO_2 regulations will be in place by the year 2010. The RO process reduces fuel gas consumption to about two thirds that of the MSF process, for an identical capacity of power generation and desalination, therefore, RO plant will easily comply with CO_2 regulations.



① MSF TYPE



② RO TYPE

Figure 9.2.2 Plot Plan for 6MGPD Desalination Plant (for Reference)

9.2.4 Economic Comparison of Systems

(1) System configuration of the process

Economy of both, MSF and RO, desalination plants shall be compared with each other totally, including power generation plants respectively. Because there is no other definitive means for the cost assessment in desalination plant, such that how to distribute MSF fuel cost between power generation and desalination, and how to determine directly a unit power-rate for RO cost which gives the cost variation. For the evaluation, it is therefore chosen the latest plant in Oman, the Ghubrah No. 5 Unit, as a benchmark for MSF, and also a simulated RO plant which produces the same outputs of electric power and product water as Ghubrah No. 5. Both plants. Namely, the same outputs are set as export of electricity 24.4 MW and transmission of product water 27,360 m³/d.

Figure 9.2.3 indicates configuration of the systems.

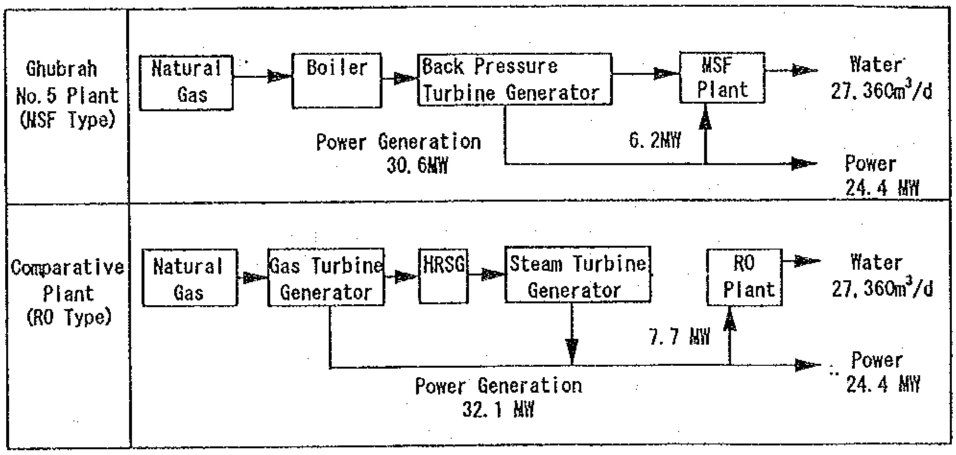


Figure 9.2.3 Configuration of MSF and RO Desalination Plants

(2) Comparison Criteria and Conditions

Given conditions for the comparison are as follows:

a. The Ghubrah No. 5 Unit's 1993 record provides information including operation hours, power generation, power consumption, electricity transmitted, water production, water transmitted and fuel gas consumption. Table 9.2.5 shows the operation record.

b. For the RO plant's power generation, power transmission and water transmission values, the Ghubrah No. 5 Unit figures are used. The consumption and fuel gas consumption are determined by assumption from average plant results as:

- Power consumption rate : 6.8 KWh/m^3
- Generating-end thermal efficiency (combined cycle): 43 % (LHV base)

c. Running costs (manpower, chemicals, consumables and spares) for MSF are not directly applicable by the Ghubrah No. 5 Unit's breakdown. Therefore, each monthly average running cost of the Ghubrah No. 5 Unit is extrapolated from the difference between the monthly average cost before the Unit was commissioned in September 1993, and the monthly average one in 1993. Table 9.2.6 shows the annual running costs for Ghubrah No. 5 Unit obtained from such trial.

d. The RO plant's running costs (manpower, chemicals, consumables and spares) is calculated by multiplying the Ghubrah No. 5 Unit's figures by correction factor. The correction factor is based on the average plant results and other reference documents. Table 9.2.6 shows these results.

Membrane exchange cost at RO plant is nominated 10 % of construction costs, with a five years service life, so the annual expense becomes 2 % of construction costs.

e. Table 9.2.7 shows the unit rate of fuel gas, oil and electric power, used to compare the economy of both processes.

We examined the above conditions to the economic performances of the following three cases.

a) Case 1: Calculation of Ghubrah No. 5 Unit

Ghubrah No. 1 Unit water production costs are calculated after determining income from transmitted electricity. The electricity unit price is RO 14/MWh, the same as the electricity billing unit price.

b) Case 2: RO plant (unit) only calculation

Water production costs are calculated using the unit price for electricity purchased, disregarding the relationship between the RO plant and power generation facilities.

c) Case 3: Calculation of combined system with RO plant (unit) and power generation plant

Income from transmitted power (as in Case 1) is added in combination of RO plant and power generation facilities. Water production costs are then calculated.

Table 9.2.8 shows the results of calculation in these three cases, using baiza/gallon, the water rate unit in Oman. The current water rates are two baiza/gallon for general use and three baiza/gallon for industrial use.

Table 9.2.5 Operation Record of Ghubrah No. 5 Plant in 1993

	Description	Unit	Ghubrah No. 5 Plant
1	Operation Hrs	hrs	7314.9
2	Water Production	m^3/y	8,106,140
3	Load Factor	%	82.54
4	Average Water Production	m^3/d	26,596
5	Power Generation	MWH/y	223,522
6	Power Generation (Output)	MW	30.56
7	Fuel Gas Consumption	Nm^3/y	110,287,396
8	Per m^3 Fuel Gas Consumption	Nm^3/m^3	13.61
9	Per kwh Fuel Gas Consumption	Nm^3/kW	0.493
10	Efficiency	%	24.2
11	Aux. Power Consumption	MWH/y	44,987
12	Aux. Power Consumption	MW	6.15
13	Power Consumption for Water Production	kWh/m^3	5.55

(Source: MEW MONTHLY REPORT)

Table 9.2.6 Comparison of Annual Operation Cost for MSF and RO types

DESCRIPTION	MSF TYPE			RO TYPE	
	STANDARD MONTHLY COST 1993 (A)	STANDARD MONTHLY COST 1992 (B)	GHUBRAH NO. 5 COST (C)	CORRECTION FACTOR (D)	ASSUMED COST (E)
UNIT (MONTH OR YEAR)	R.O./M	R.O./M	R.O./Y	R.O./Y	R.O./Y
COST OF MAN POWER	111,305	99,804	138,012	0.50	69,006
COST OF CHEMICAL USED	37,514	30,880	79,608	1.30	103,490
COST OF CONSUMABLES	31,699	26,798	58,812	1.00	58,812
COST OF SPARES USED	52,284	31,330	251,448	1.00	251,448
COST OF MEMBRANE REPLACEMENT	0	0	0		548,000
COST OF EQUIP. DEPRECIATION	579,937	400,931	2,148,072		1,030,756

Notes 1. (C) = {(A) - (B)} x 12
2. (E) = (C) x (D)

Source: MEW MONTHLY REPORT FOR ITEMS (A) & (B)

Table 9.2.7 Cost of Utilities

FUEL GAS COST	R.O./Nm^3	0.0283389
FUEL GAS CALORIC VALUE	Kcal/Nm^3	7,209
FUEL OIL COST	R.O./l	0.108
COST OF POWER USED	R.O./MWH	14.00

Source: MEW

Table 9.2.8 Comparison of Water Production Costs by Type of Plants

DESCRIPTION		UNIT	CASE 1	CASE 2	CASE 3
			DUAL PURPOSE MSF (GUBRAH NO. 5)	6 MGPD ROPLANT	
			DESAL. & POWER	DESAL. ONLY	DESAL. & POWER
DATA (PER YEAR EXCEPT FOR NO. 1)					
1	INSTALLATION COST	R.O.	49,000,000	28,770,000	38,770,000
2	EXPORTED WATER	M^3	8,106,140	8,106,140	8,106,140
3	FUEL GAS CONSUMP TION (PDO FIG)	M^3	110,287,396	0	64,823,692
4	FUEL OIL CONSUMPTION	LITRES	1,092,960	0	0
5	POWER CONSUMED	MWH	44,987	58,364	58,364
6	POWER GENERATED	MWH	223,522	0	236,900
EXPENSES PER YEAR					
1	FUEL GAS COST	R.O./Y	3,121,133	0	1,834,510
2	FUEL OIL COST	R.O./Y	118,040	0	0
3	COST OF POWER USED	R.O./Y	-2,499,500	817,099	-2,499,500
4	COST OF MAN POWER	R.O./Y	138,012	69,006	69,006
5	COST OF CHEMICAL USED	R.O./Y	79,608	103,490	103,490
6	COST OF CONSUMABLES	R.O./Y	58,812	58,812	58,812
7	COST OF SPARES USED	R.O./Y	251,448	826,848	826,848
8	COST OF CAPITAL RECOVERY	R.O./Y	3,920,000	2,300,000	3,100,000
9	TOTAL COST	R.O./Y	5,187,553	4,175,255	3,493,166
COST PER M^3 FOR WATER EXPORT					
1	FUEL GAS COST	BAIZA/M^3	385.6	0.0	217.9
2	FUEL OIL COST	BAIZA/M^3	14.6	0.0	0.0
3	COST OF POWER USED	BAIZA/M^3	-308.3	100.8	-308.3
4	COST OF MAN POWER	BAIZA/M^3	17.0	8.5	8.5
5	COST OF CHEMICAL USED	BAIZA/M^3	9.8	12.8	12.8
6	COST OF CONSUMABLES	BAIZA/M^3	7.3	7.3	7.3
7	COST OF SPARES USED	BAIZA/M^3	31.0	102.0	102.0
8	COST OF EQUIP. DEPRECIATION	BAIZA/M^3	483.6	283.7	382.4
9	TOTAL COST	BAIZA/M^3	640.0	515.1	430.9
10	EXPORT WATER COST	BAIZA/GAL	2.91	2.34	1.96

9.2.5 Overall evaluation

Table 9.2.9 includes all the comparison results of both plants summarizing their reliability, technical and economical evaluations.

Based on these results, it can say that;

- MSF plant is superior in reliability due to the many operating records while it is not so economical and takes longer delivery time.
- Applicability of RO plant will finally depend on the priority (to MSF plant) in economy, considering the recent process reliability.

Therefore, we decided to evaluate further in details the difference between them in economics estimated in 2010 at Barka Plant. And, conceptual design was conducted to evaluate both process plants.

Table 9.2.9 Result of Evaluation in Comparison between MSF and RO Processes

Item	MSF Process	RO Process
1. RELIABILITY OF OPERATION AND MAINTENANCE	High reliability is confirmed through the operation record	Past Experience is few; some failures occurred; but reliability is significantly improving
2. ECONOMICS	Ghubrah No. 5 Unit (with Power Generation Plant)	At same capacity plant as MSF (with Power Ge.)
(a) Construct. cost	49 R.O. (127 M$)	36.1 R.O. (93.7 M$)
(b) Water pro. cost	2.91 baiza/gallon	1.96 baiza/gallon (same desali. & ele. outp.)
3. DELIVERY TIME	MSF only: 2.5 years Power plant: 3 years (each about)	RO: about 2 years (independently)
4. OPERATION RECORD	Up to 65 % of large scale plants; Single max. 45,500 m^3/d Max. plant 900,000 m^3/d	Operating in 1991, total about 900,000 m^3/d Max. plant 56,000 m^3/d Under construction Max. plant 128,000 m^3/d
5. OPERATION	Constraint tied up with power generation	Operation as free due to each independence of power generation and desalination plant
6. ENVIRONMENTALS	With same capacity as RO, for product water and power output, fuel consumption is about 1.5 times RO process and much CO_2 effluents	Advantage of fuel consumption saving to about 2/3 of MSF process, including CO_2 effluence reduction

9.2.6 Advantages of RO Process for Barka Project

Additionally, it can say the following two advantages of RO process for the Barka Project, comparing to other Gulf Coast Countries.

(1) Natural gas Price is 2.6 \$/MBTU dearer than about 1 \$/MBTU in GCC so that MSF is relatively expensive for much fuel consumption.

(2) Sea water salinity is about 40,000 ppm less than 45,000 ppm in the Gulf or Red Sea, and it contributes cost reduction including capital one.

An assumed correlation of natural gas price and water production cost is shown as Figure 9.2.4. It is suggested, in case for other GCC where the gas price around 1 \$/MBTU, MSF process will be more recommendable as the production cost nearly equal to each other, in conjunction with the scale merit of larger plant capacity.

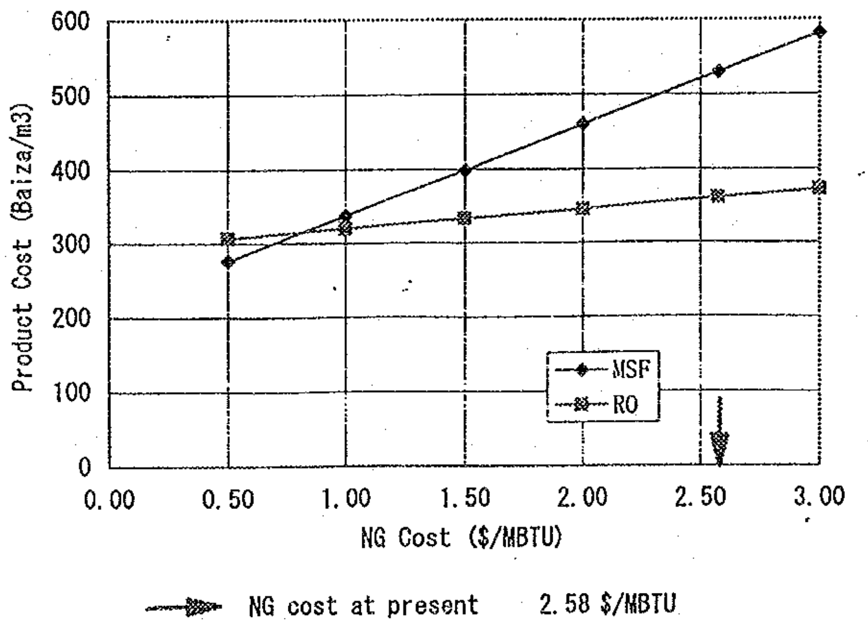


Figure 9.2.4 Product Water Cost vs NG Cost

9.3 Conceptual Design of Desalination Plant

As mentioned in Clause 9.2.5, we decided to perform further the conceptual design of power generation plant and desalination plant in both cases, the MSF and RO processes, at Barka, in order to pursue their economic comparison entirely.

Major applicable items, presupposition etc. on their conceptual design are as follows:

As mentioned in Clauses 5.5.2 and 5.5.5,

- MSF plant shall be built with 2 units at the same time, in four stages to finally 8 units, with 63,600 m^3/d (31,800 m^3/d/unit) per each stage.

- RO plant shall be composed of one pre-treatment facility and 8 RO modules with 63,600 m^3/d per each stage. High pressure pump and RO module are divided into 8 units.

Result of the conceptual design is respectively illustrated in Clause 9.4, for MSF process, and in Clause 9.5, of RO process, according to the above conditions. There are included the cost and schedule of construction as key items, too.

9.4 Conceptual Design of MSF Desalination Plant

9.4.1 Design Base

(1) Tube configuration of the evaporator condenser

Cross tube type arrangement will be adopted.

(2) Scale prevention system

A chemical injection method of a high-temperature model is adopted. The top brine temperature will be set at 107°C to correspond to the latest design temperature.
Ball cleaning system on load cleaning is also applied.

(3) Performance ratio

In this project, performance ratio of 8 is applied, and the reason are explained in Appendix 9.3.

(4) Brine recirculation pump system

Although the Ghubrah No. 5 Unit applied the steam driven system, the electric motor driven system is more widely used in many plants and offers a higher degree of reliability, accordingly this project will have the electric motor driven system.

(5) Concentration ratio

The 1985 F/S applied a TDS (total dissolved solids) level of 65,000 mg/l. This value will be used as it is almost the same as that of the Ghubrah No. 5 plant.

(6) Number of evaporator stages

The 1985 F/S used 23 stages, and this number presents no particular problems, it will be used for this project.

(7) Number of tier of evaporator

Both single and double tier evaporator have been applied for the cross tube type evaporator.

For double tier, as the brine heater, deaerator, ejector have to be arranged in one group at one end of evaporator, this results in complicated and long piping layout.

On the contrary, for single tier type, larger area is required for construction but maintenance is easy as compared with the double tier type.

We will adopt the single tier type for this project.

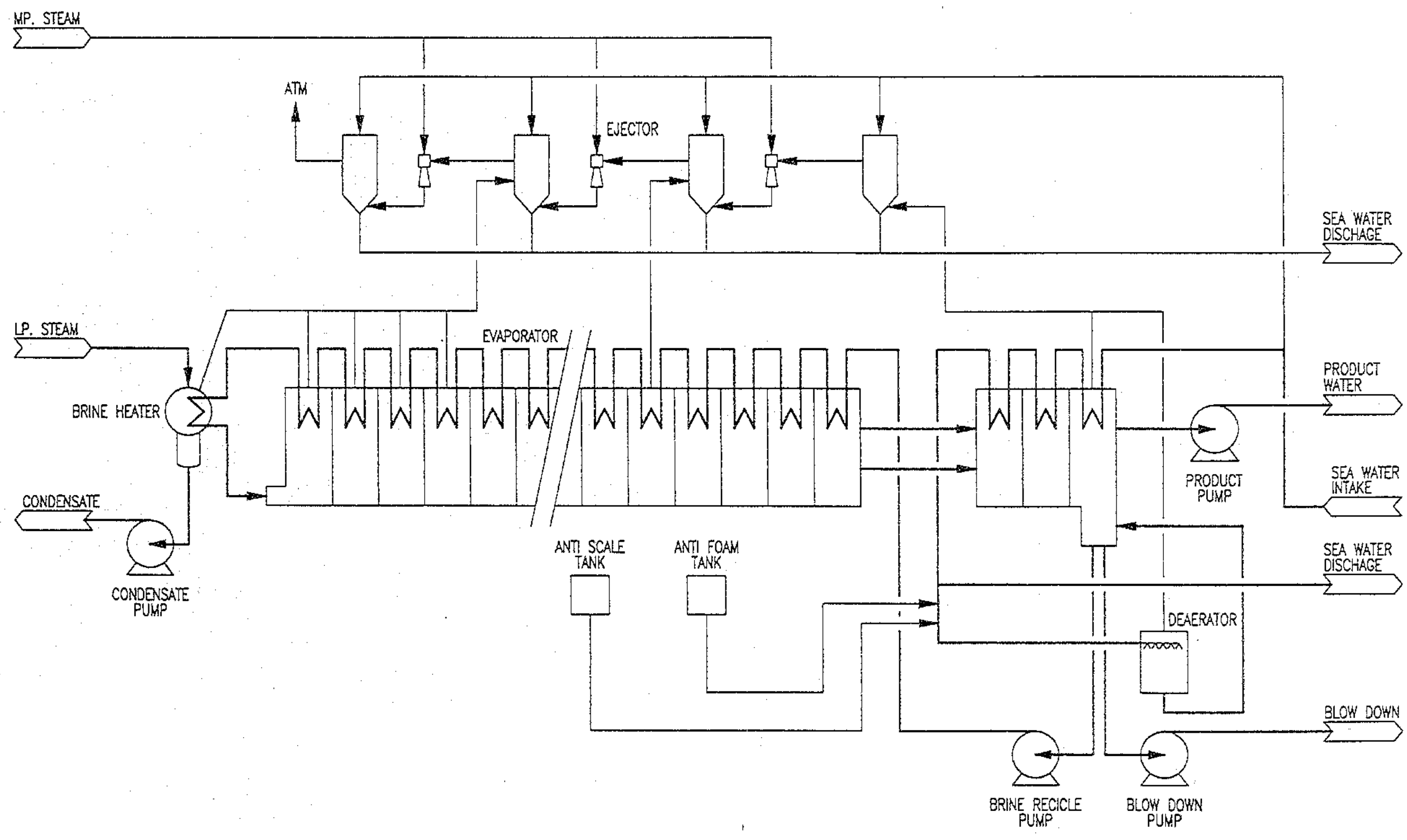


Figure 9.4.1 Desalination Plant (MSF Process) Flow Chart

OBD00001

9.4.2 Plant Specification

Type	Cross tube type multi-stage flush type
Total Production Capacity	254,000 m^3/d
Number of Unit	31,800 m^3/d x 8 units
Process type	Brine recirculation type
Scale prevention	Anti scale agent injection and vall cleaning
Evaporator stage number	Heat Recovery Section 20 stages Heat Rejection Section 3 stages Total 23 stages
Performance ratio	8.0
Brine top temperature	107°C

9.4.3 Outline of Process

(1) Process Flow

Process flow is shown in Figure 9.4.1.

Sea water is introducted to the heat rejection section as cooling water by sea water supply pump.
A portion of sea water is flown to ejector condenser and discharged into cooling sea water outlet line from the heat rejection section. Above ejector system removes noncondensable gases and maintain vacuum in evaporator.

Sea water from the heat rejection section is mainly discharged into the discharge culvert and the rest is combined with brine through deaerator as make-up water. Anti-scale agent and anti-form agent are injected into make up water for prevention of scale by metering pumps.

The greater part of brine at the last stage chamber is introduced into the last condenser tube of the heat recovery section by brine recycle pump.

At each stage recycle brine gains the latent heat of flash vapor condensing on the external tube surfaces and its temperature increase as it passes through the heat recovery condensers to the first stage.

Preheated recycle brine from the first stage condenser is then fed to the brine heater where it is further heated by steam.
Heated brine is introduced into the first stage flash chamber and the flash evaporation is repeated from stage to stage by pressure difference per stage.

In addition, a part of brine is discharged out of evaporator before combined with the make-up water by blow down pump to keep brine salinity constant.

Medium pressure steam and low pressure steam from the steam turbine of the power plant are utilized for venting system ejector and the brine heater respectively.

Distillate is produced by the repeated flash evaporation from stage to stage and delivered from the last of the evaporator to product water treatment by product water pump.

(2) Post treatment system

This treatment system is useful for corrosion protection of reservoir and transmission facilities and also palatable for drinking water.
The Product water of each desalination plant is pumped up to the absorber.
The CO_2 gas in the exhaust gas from the evaporator and deaerator is compressed by compressors and is contacted with the product water in the absorber.

Then the CO_2 rich water in the absorber passes the limestone filter. In the filter, the ions of Ca^{++} and CO_3^- are made by $CaCO_3$ in limestone and the CO_2 gas.

The treated water is chlorinated and pH is adjusted to 7.0 ~ 8.5 by injection of soda ash.

9.4.4 Equipment Specification (per Unit)

The Production capacity per Unit is 31,800 m^3/day.

(1) Evaporator (1/Unit)

Heat Recovery Section

Type	:	Cross tube & rectangular box type
Number of Stages	:	20 stages
Materials:		

Shell & Partition Plate		
Stage No. 1 - No. 6	:	Carbon steel + 316 L SS cladding
Stage No. 7 - No. 20	:	Carbon steel + coating
Tube sheet	:	90/10 Cu-Ni
Tube		
Stage No. 1 - No. 4	:	70/30 Cu-Ni
Stage No. 5 - No. 20	:	Aluminum brass
Water box	:	Carbon steel + coating

Heat Rejection Section

Type	:	Cross tube & rectangular box type
Number of Stages	:	3 stages
Materials:		
Shell & Partition Plate	:	Carbon steel + coating
Tube sheet	:	90/10 Cu-Ni
Tube	:	Titanium
Water box	:	Carbon steel + 90/10 Cu-Ni cladding

(2) Brine Heater

Type	:	Horizontal, shell & tube type exchanger
Quantity	:	1
Materials:		
Shell	:	Carbon Steel
Tube	:	70/30 Cu-Ni
Tube sheet	:	70/30 Cu-Ni
Water box	:	Carbon steel + 90/10 Cu-Ni cladding

(3) Deaerator

Type	:	Vacuum packed tower type
Quantity	:	1
Performance	:	Dissolved oxygen max. 20 ppb
Material:		
Shell	:	Carbon Steel + 316L SS cladding

(4) Main process pumps

1) Brine Recycle Pump

Type	:	Vertical mixed flow pump with barrel

Quantity	:	1
Capacity	:	15,000 m^3/hr
Total head	:	50 m
Driver	:	Electric motor
Material:		
Shell	:	Ni-resist
Impeller	:	Stainless cast steel
Shaft	:	Stainless steel
Barrel	:	FRP

2) Brine Blow-down Pump

Type	:	Vertical mixed flow pump with barrel
Quantity	:	1
Capacity	:	1,813 m^3/hr
Total head	:	20 m
Driver	:	Electric motor
Material:		
Casing	:	Ni-resist
Impeller	:	Stainless cast steel
Shaft	:	Stainless steel
Barrel	:	FRP

3) Product Water Pump

Type	:	Vertical mixed flow pump
Quantity	:	2 (working: 1, stand-by: 1)
Capacity	:	1,500 m^3/hr
Total head	:	30 m
Driver	:	Electric motor
Material:		
Casing	:	Stainless cast steel
Impeller	:	Stainless cast steel
Shaft	:	Stainless steel

4) Condensate Pump

Type	:	Horizontal volute
Quantity	:	2 (working: 1, stand-by: 1)
Capacity	:	198 m^3/hr
Total head	:	35 m
Driver	:	Electric motor

Material:

Casing	:	Cast steel
Impeller	:	Stainless cast steel
Shaft	:	Stainless steel

9.5 Conceptual Design of RO Desalination Plant

9.5.1 Design Base

In carrying conceptual design, basic philosophy are described as follows.

(1) Pretreatment of Sea Water

The particulate suspended in the raw sea water must be removed in order to prevent the degradation of the RO module. This is performed with direct filtration of the raw sea water.

There are two type of filtration, the gravity filter and the pressurized filter. In Oman, at the Sur Desalination Plant (RO Process), the pressurized filter is used.

However, at large desalination plants, the gravity filter is used in general, so gravity filter is recommended for this project.

In addition to the removal of particulate, the seawater is also treated by chlorination and neutralization for pH adjustment. etc.

(2) Recovery Rate

The consumption of energy will vary with the size and capacity of the desalination process since in the reverse osmosis process sea water is forced to pass through a membrane using the osmotic pressure of the sea water, and the rate of recovery can be calculated with the following formula:

$$\text{Recovery Rate \%} = \frac{\text{Desalinated Water } m^3/d}{\text{Sea Water Supplied } m^3/d} \times 100$$

Old type RO recovery rate was about 35 % because the withstanding pressure limit of membrane was low, and there was concern over gypsum scale ($CaSO_4 \cdot 2H_2O$) formation. But this has since been improved to more than 40 % with the improvement of technique. The Sur Desalination Plant, using the RO method, has recorded recovery rates exceeding 40 %. The salinity of the sea water off the coast of Oman is comparatively lower than that in the

Arabian Gulf and Red Sea. A recovery rate of 40 % will therefore be appropriate, and will be used in the conceptual design.

(3) Energy Recovery Rate

In the RO process, sea water will be pressurized to about 60 ~ 80 kg/cm^{3}G, and the water pressure at the exit of the RO module is maintained at about the same. At large desalination, a recovery turbine is to reclaim energy.

Energy will be reclaimed in this project with suitable equipment.

9.5.2 The Plant Specification

(1) Plant Specification

- Total Production Capacity — 254,000 m^3/day
- Production Capacity per Unit — 63,600 m^3/day
  (The project will be divided into 4 stages, and each stage will be designated as a [Unit] for the total production capacity)
- Pretreatment — chlorinate,
  gravity filtration (coagulation filter)
  pH adjustment,
  Cl_2 decomposition
  safety filter (cartridge filter)
- High Pressure Pump (per Unit) — 950 m^3/h x 8 pumps combined with energy recovery turbine
- RO Module — 8 trains
- Post Treatment — chlorination
  pH adjustment with $Ca(OH)_2$

(2) Operation Condition

- Chlorine Injection — 1 ~ 2 ppm as Cl_2
- Sand Filtration Velocity — less than 8 m/h
- Pretreated Water FI — < 3
- High Pressure Pump Pressure — Max. 70 kg/cm^{2}G
- Recovery Rate — 40 %
- Power Consumption — less than 7.2 kWh/m^3

9.5.3 Outline of Process

A simplified process flow is shown in Figure 9.5.1.

The RO Desalination Plant consists of three sections; pre-treatment section, reverse-osmosis section, and the post-treatment section.

The sea water is at first pretreated by Cl_2 for disinfection and mixed with such as $FeCl_3$, then passes through the sand filter (dual filter). Suspended matters in the sea water are removed in the sand filter. The filter consists of dual layers of anthracite and the lower layer of fine sand. The sand filter is regenerated periodically by backwashing.

The filtered sea water runs next through an adjusted safety filter where remaining minute particulate in the sea water is removed to prevent clogging the membrane.

The sea water is finally pumped by the high pressure pump at the pressure of 60 - 70 kg/cm^2 and passes through the reverse-osmosis module where 40 % of the water is permeated through the membrane. The remaining 60 % of brine is discharged as waste through energy recovery turbine to reduce energy consumption.

Permeated water by RO plant is almost suitable for drinking water, and $Ca(OH)_2$ is dosed for pH adjustment, and sterilized by chlorination. Then sulfuric acid for pH adjustment and a reductant to neutralize residual chlorine are dosed to the filtered sea water.

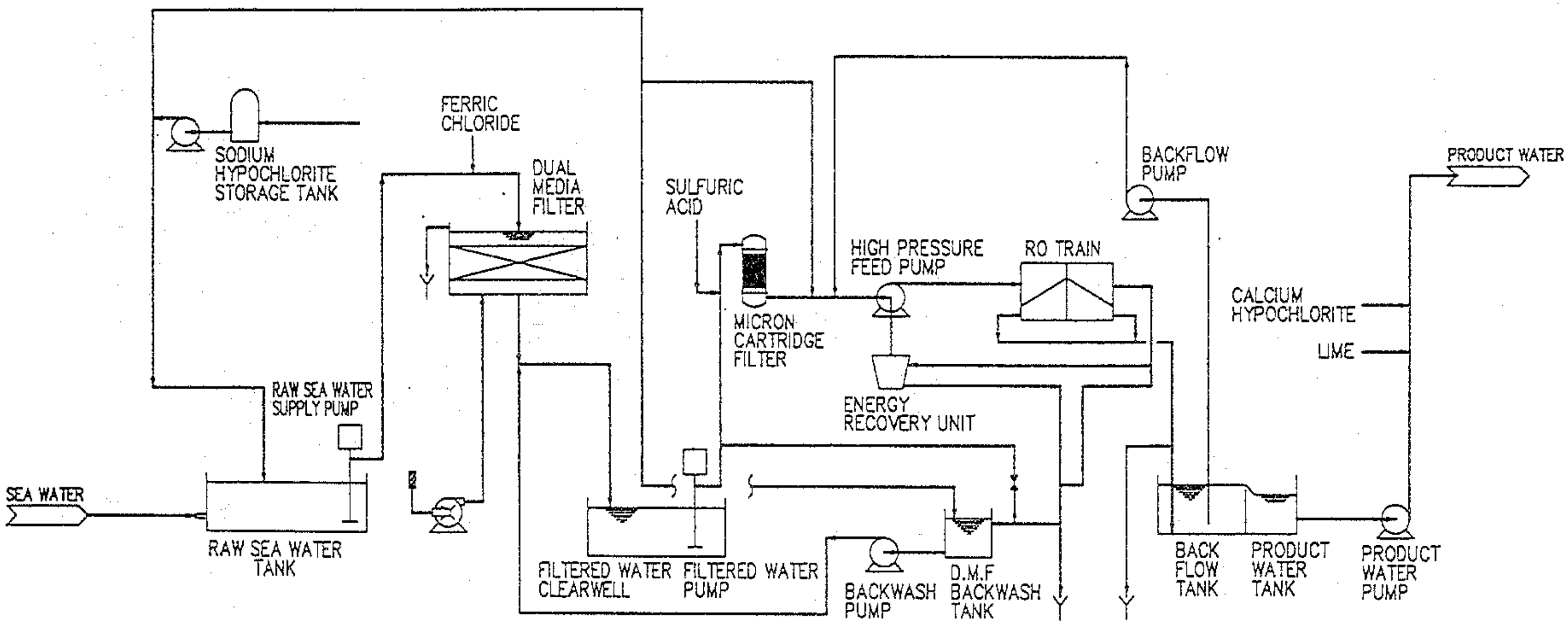


Figure 9.5.1 Desalination Plant (RO Process)

DESALINATION PLANT
(RO PROCESS)
FLOW SHEET

9.5.4 Equipment Specification (per Unit)

The production capacity per Unit is 63,000 m^3/day.

(1) RO Module unit

Type	:	Reverse Osmosis Module
Number of Trains	:	8
		by vender

(2) Sand Filter Bed

Type	:	Gravity type
Material	:	Reinforced concrete

(3) Safety Filter

Type	:	Cartridge type
Quantity	:	10 (Working: 8, Standby: 2)
Material:		
Body	:	FRP
Element	:	Polypropylene

(4) Main Pumps

a. Seawater Supply Pump

Type	:	Vertical mixed flow
Quantity	:	3 (Working: 2, Standby: 1)
Capacity	:	3,800 m^3/h
Head	:	20 m
Driver	:	Electric motor
Materials:		
Casing	:	Stainless steel casting
Impeller	:	Stainless steel casting
Shaft	:	Stainless steel

b. Filtered Water Pump

Type	:	Vertical mixed flow
Quantity	:	3 (Working: 2, Standby: 1)

Capacity	:	3,800 m^3/h
Head	:	40 m
Driver	:	Electric motor
Materials:		
Casing	:	Stainless steel casting
Impeller	:	Stainless steel casting
Shaft	:	Stainless steel

c. High Pressure Pump

Type	:	Horizontal volute
Quantity	:	8
Capacity	:	950 m^3/h
Head	:	700 m
Driver	:	Electric motor
Materials:		
Casing	:	Stainless steel casting
Impeller	:	Stainless steel casting
Shaft	:	Stainless steel

d. Energy Recovery Unit

Type	:	Francis type
Quantity	:	8
Capacity	:	570 m^3/h
Pressure:		
Suction	:	570 m
Discharge	:	50 m
Materials:		
Casing	:	Stainless steel casting
Impeller	:	Stainless steel casting
Shaft	:	Stainless steel

e. Product Water Pump

Type	:	Horizontal volute
Quantity	:	3 (Working: 2, Standy: 1)
Capacity	:	1,520 m^3/h
Head	:	40 m
Driver	:	Electric motor

Materials:

Casing	:	Stainless steel casting
Impeller	:	Stainless steel casting
Shaft	:	Stainless steel

(5) Chemicals dosing unit

- Cl_2 Injection
- $FeCl_3$ Injection
- Coagulant Injection
- H_2SO_4 Injection
- Sodium Bisulfate Injection

9.5.5 Management of RO Plant

In RO process plant, it may be maintained without plant shutdown, because rotating equipments of the plant are provided with standby set. And also, gravity sand filters consist of 12 cells including 1 standby cell so that they can be maintained and inspected during continuos operation.

Major factors affect RO plant availability are three; ① HP pump maintenance, ② membrane replacement, ③ plant shutdown due to deterioration of pretreated water quality. For these points, the two formers are resolved by partial plant shutdown, and the third one could be entirely prevented through appropriate system design, manufacturing and installation for pre-treatment corresponding to elaborate raw sea water sampling analysis.

Thus, availability of RO process is always expectable more than 95 % at present. Depending on this feature, total water supply system will be able to ensure the reliability by adjusting well water pumping against seasonal demand fluctuation.

Table 9.5.1 and Figure 9.5.2 are anticipated operation of Ghubrah and Barka plant in consideration with seasonal fluctuation and maintenance in 2010.

As shown in Figure 9.5.2, the said water supply system would be managed surely in good order with sufficient allowance to water demand.

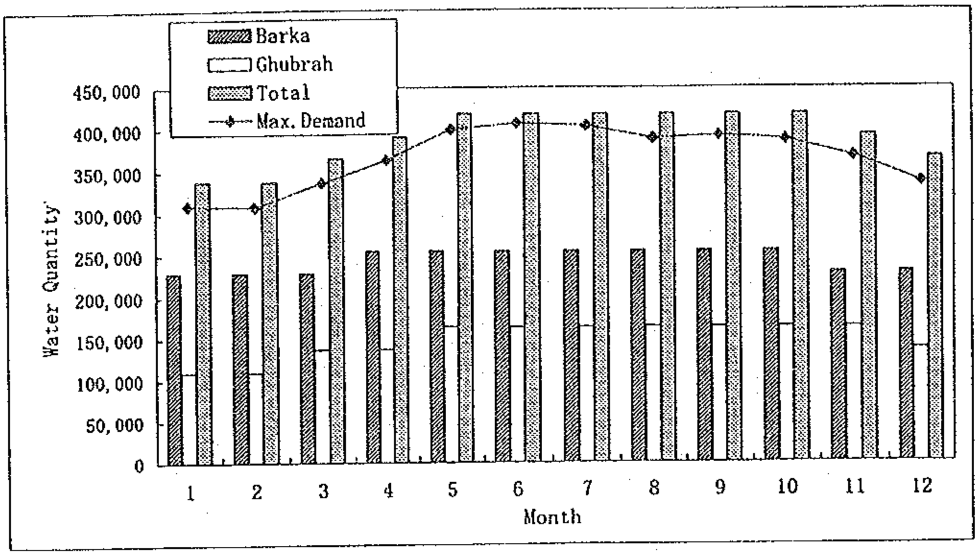


Figure 9.5.2 Anticipated Operation of Desalinatio Plant in 2010

Table 9.5.1 Anticipated Operation of Desalination Plant in 2010

Month	Season factor	Max. Demand	No. of unit operated		Water production		
			Barka	Ghubrah	Barka	Ghubrah	Total
1	84.5	309,722	3.6	4	228,960	109,200	338,160
2	84.1	308,287	3.6	4	228,960	109,200	338,160
3	91.9	336,860	3.6	5	228,960	136,500	365,460
4	99.0	363,168	4	5	254,400	136,500	390,900
5	108.9	399,457	4	6	254,400	163,800	418,200
6	111.0	407,026	4	6	254,400	163,800	418,200
7	110.2	403,955	4	6	254,400	163,800	418,200
8	106.1	389,145	4	6	254,400	163,800	418,200
9	106.9	392,103	4	6	254,400	163,800	418,200
10	105.7	387,424	4	6	254,400	163,800	418,200
11	100.0	366,848	3.6	6	228,960	163,800	392,760
12	91.6	336,005	3.6	5	228,960	136,500	365,460
Average	100.0	366,667	3.83	5.42	243,800	147,875	391,675

Note: Season factor ; Monthly average supply / Yearly average supply
Max. Demand ; Yearly average supply x Season factor x 1.1
1.1 ; Margin for daily fluctuation