

Appendices

APPENDIX -A

A.1 EFFECT OF AIR CONDITIONER MOTOR LOADS ON SYSTEM VOLTAGE DURING TRANSMISSION SYSTEM FAULT

The load impedance \( Z_{load} \) is the combined impedance of the induction motor and other loads. The simplified expression of load impedance considering only motor loads neglecting the other loads (motor loads comprises a high percentage of the utility load), can be written as

\[
Z_{load} = r + j X
\]  (A.1)

where \( r \) is the resistance and \( X \) is the reactance of the winding and \( 's' \) is the slip of the motor.

Under normal operating condition, the value of this slip reduces to zero thereby, the real part of the \( Z_{load} \) reaches infinity and the motor loads draws minimum current. The motor torque \( T \) is directly proportional to the square of the system voltage. Whenever the voltage across such load drops, the torque decreases and the slip increase exponentially towards a stall condition. This result in the significant decrease of \( Z_{load} \) due to the decrease of its real component and the motor draws maximum current. Based on the inertia and hence variation of speed to voltage dip, the induction motor can be classified into two types namely (i) Robust motors (ii) Prone to stall motor [Mozina (2007)].

The robust motor will have high inertia and tends to maintain their speed during short periods of voltage dip. On the other hand the speed of low inertia induction motors tends to vary rapidly as a result of voltage dip. These types of motors are referred as prone to stall motor. Air conditioning motors are of this type [Mozina (2007)]. Even if full voltage is restored then also the rotor of robust motor cannot re-accelerate to its full speed. If the fault is sustained due to delayed protection gear, the robust motor will also stall (or) slow down. The effective impedance of a block of mixed “prone to stall” and
robust motor loads \( (Z_{\text{load}}) \) tends to decrease during prolonged faults. However, during a fault, transmission lines and transformer are usually tripped by the protective gears this will eventually increases the system impedance. Therefore the system will reach a new steady state post fault condition with lower impedance loads and higher system impedance. Due to lower impedance, the motor load draws maximum current from the remote source. However, the current has to flow through the transmission line with higher impedance this will eventually increases the voltage drop and therefore lead to voltage collapse.
APPENDIX-B

For the power system to be stable, the electrical output of generating unit and the electrical load on the system should match continuously. The load characteristics have significant impact on the system stability [Berglund et al (1974)].

B.1 POWER SYSTEM LOADS

Power system loads consists of large number of devices like motors, heaters, compressors, furnaces, lamps, refrigerators and so on. However, the combination of these loads varies, which depends on many factors, such as, time (hour, day and season), weather condition, and state of the economy. Therefore, modeling of loads is very complicated. This needs a significant amount of simplification [Berglund et al (1974)].

B.2 LOAD MODELLING

The load model can be broadly classified into two types: static models and dynamic models. In this section a brief description about the static load model have been presented.

B.2.1 STATIC LOAD MODEL

In this load model, the load characteristics at any instant of time can be expressed as algebraic functions of the bus voltage magnitude and system frequency at that instant [Berglund et al (1974)]. The active and reactive power components of the load are expressed separately.

*Exponential model*

The exponential model represents the voltage dependency of load characteristics and it can be expressed as follows:

\[ P = P_0 (\bar{V})^a \]  
\[ Q = Q_0 (\bar{V})^b \]  

(B.1)
where $\bar{V} = \frac{V}{V_0}$; $P$ and $Q$ are active and reactive components of the load when the bus voltage magnitude is $V$. Here, $V_0$, $P_0$ and $Q_0$ refer to the initial operating conditions. Moreover, $a$ and $b$ are the parameters of this model. By assigning the values for $a$ and $b$ equal to 0, 1 or 2, the model characterizes into constant power, constant current, or constant impedance, respectively. However, the $a$ and $b$ values for composite loads depend on the collective characteristics of load components. The summary of data available in the literature on voltage dependency of load was given in [Estergalyos, et al (1978)]. In [Lindsay and Shenoy (1978)] and [Breuer et al (1964)] the results of measurements which provides information about the variation of the load characteristics with time of day, season, and/or temperature were presented.

In the absence of specific information, the most commonly accepted static load model is to represent active power as constant current (ie., $a=1$) and the reactive power as constant impedance (ie., $b=2$) [Estergalyos et al (1978)].

**Polynomial model**

This is another load model which has been widely used to represent the voltage dependency of loads. It can be expressed as

\[
P = P_0 \left[ p_1 \bar{V}^2 + p_2 \bar{V} + p_3 \right]
\]

\[
Q = Q_0 \left[ q_1 \bar{V}^2 + q_2 \bar{V} + q_3 \right]
\]

As this model consists of constant impedance ($Z$), constant current ($I$) and constant power ($P$) components, it is generally known as the ZIP model [Berglund et al (1974)]. The parameters of the model are the coefficients $p_1$ to $p_3$ and $q_1$ to $q_3$, which defines the proportion of each component.

The frequency dependency of load characteristic can be included in the exponential or the polynomial model by multiplying the model by a factor as follows
\[ P = P_0 (\bar{V})^a (1 + K_{pf} \Delta f) \]  \hspace{1cm} (B.3)

\[ Q = Q_0 (\bar{V})^b (1 + K_{qf} \Delta f) \]

\[ P = P_0 \left[ p_1 \bar{V}^2 + p_2 \bar{V} + p_3 \right] (1 + K_{pf} \Delta f) \]  \hspace{1cm} (B.4)

\[ Q = Q_0 \left[ q_1 \bar{V}^2 + q_2 \bar{V} + q_3 \right] (1 + K_{qf} \Delta f) \]

where \( \Delta f \) is the frequency deviation \( (f - f_0) \), \( K_{pf} \) ranges from 0 to 3 and \( K_{qf} \) ranges from -2 to 0 [Estergalyos et al (1978)].

A comprehensive static model which accommodates several forms of load can be expressed as [Kimbark (1996)].

\[ P = P_0 \left[ P_{ZIP} + P_{EX1} + P_{EX2} \right] \]  \hspace{1cm} (B.5)

where \( P_{ZIP} = p_1 \bar{V}^2 + p_2 \bar{V} + p_3 \); \( P_{EX1} = P_4 (\bar{V})^{a1} (1 + K_{pf1} \Delta f) \); \( P_{EX2} = P_4 (\bar{V})^{a2} (1 + K_{pf2} \Delta f) \).

The reactive component of the load can also be expressed in the similar manner.
APPENDIX-C

In the second strategy of load shedding presented in the fourth chapter of this thesis, the buses for load shedding are selected based on the sensitivity of the critical line of the system. The line voltage stability index is used to identify the critical line of the system. The expressions for real and reactive power at the receiving end of a transmission system are used to obtain the expression for line voltage stability index and it is derived in this section.

C.1 EXPRESSION FOR REAL AND REACTIVE POWER AT THE RECEIVING END

\[
\begin{align*}
|V_S| \angle \delta & \quad |V_R| \angle 0 \\
S_S &= P_S + jQ_S \\
S_R &= P_R + jQ_R
\end{align*}
\]

Fig. C.1 Single line diagram of power system transmitting real and reactive power to the load

where

\( V_S \) is the sending end voltage with a load angle of \( '\delta' \)

\( V_R \) is the receiving end voltage

\( S_S \) is the sending end complex power

\( S_R \) is the receiving end complex power

but we know

\[
S_S = P_S + jQ_S = V_S I_S^* \\
S_R = P_R + jQ_R = V_R I_R^*
\]

(C.1)

(C.2)

\[
\begin{bmatrix}
V_S \\
I_S
\end{bmatrix} =
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
V_R \\
I_R
\end{bmatrix}
\]

(C.3)

\[
V_S = AV_R + BI_R
\]

(C.4)
\[ I_S = CV_R + DI_R \]  
\[(C.5)\]

from (C.4) and (C.5)
\[ I_R = V_S / B - AV_R / B \]
\[ \therefore I_S = CV_R + D\left[ V_S / B - AV_R / B \right] \]  
\[(C.6)\]

substituting (C.6) in (C.5) we get
\[ I_S = DV_S / B - V_R / B \]  
\[(C.7)\]

Let
\[ A = |A| \angle \alpha, \quad D = |D| \angle \alpha, \quad B = |B| \angle \beta \]
then
\[ I_R = \frac{|V_S|}{|B|} \angle (\delta - \beta) - |A| \left| \frac{V_R}{B} \right| \angle (\alpha - \beta) \]  
\[(C.8)\]
\[ I_S = |D| \left| \frac{V_S}{|B|} \right| \angle (\alpha + \delta - \beta) - \frac{|V_R|}{|B|} \angle - \beta \]  
\[(C.9)\]

find \( I_S^* \) & \( I_R^* \)
\[ I_R^* = \frac{|V_S|}{|B|} \angle (\beta - \delta) - |A| \left| \frac{V_R}{B} \right| \angle (\beta - \alpha) \]  
\[(C.10)\]
\[ I_S^* = |D| \left| \frac{V_S}{|B|} \right| \angle (\beta - (\alpha + \delta)) - \frac{|V_R|}{|B|} \angle \beta \]  
\[(C.11)\]

Complex receiving end voltage can be written as
\[ S_R = V_R I_R^* \]
\[ S_R = \left| \frac{V_R}{|B|} \right| \angle (\beta - \delta) - \frac{|A|}{|B|} \left| \frac{V_R}{B} \right|^2 \angle (\beta - \alpha) \]  
\[(C.12)\]

Complex sending end voltage can be written as
\[ S_S = V_S I_S^* \]
\[ S_S = \left| \frac{D|V_S|}{|B|} \right|^2 \angle (\beta - \alpha) - \frac{|V_S|}{|B|} \left| \frac{V_R}{B} \right| \angle \delta + \beta \]  
\[(C.13)\]

As \( V_S \) and \( V_R \) are per phase values. Eqs. (C.13) and (C.12) are sending and receiving end complex power per phase. If equation (C.13) and (C.12) are expressed in
3-Φ then $V_s$ and $V_r$ should be line kV. Therefore the 3-Φ receiving end complex power can be written as

$$S_{R(3-Φ)} = 3 \left( \frac{|V_s||V_s|}{\sqrt{3}|B|} \angle (β - δ) - |A||V_r|^2 \angle (β - α) \right) \quad (C.14)$$

$$S_R = \frac{|V_s||V_s|}{|B|} \angle (β - δ) - \frac{|A||V_r|^2}{|B|} \angle (β - α) \quad (C.15)$$

Similarly the 3-Φ sending end complex power can be written as

$$S_{S(3-Φ)} = \frac{|D||V_s|^2}{|B|} \angle (β - α) - \frac{|V_s||V_r|}{|B|} \angle δ + β \quad (C.16)$$

From the 3-Φ complex receiving end power given in Eq. (C.15) we can write the 3-Φ real and reactive power

$$P_R = \frac{|V_s||V_s|}{|B|} \cos(β - δ) - \frac{|A||V_r|^2}{|B|} \cos(β - α) \quad (C.17)$$

$$Q_R = \frac{|V_s||V_s|}{|B|} \sin(β - δ) - \frac{|A||V_r|^2}{|B|} \sin(β - α) \quad (C.18)$$

Similarly for sending end we can write the 3-Φ real and reactive power

$$P_S = \frac{|D||V_s|^2}{|B|} \cos(β - α) - \frac{|V_s||V_r|}{|B|} \cos(δ + β) \quad (C.19)$$

$$Q_S = \frac{|D||V_s|^2}{|B|} \sin(β - α) - \frac{|V_s||V_r|}{|B|} \sin(δ + β) \quad (C.20)$$

The receiving end real power $P_R$ is maximum when δ is equal β.

Substituting the condition $δ = β$ in Eq.(C.17), the maximum value of receiving end real power can be obtained as

$$[P_R]_{max} = \frac{|V_s||V_s|}{|B|} - \frac{|A||V_r|^2}{|B|} \cos (β - α) \quad (C.21)$$

Value of $Q_R$ when $P_R = (P_R)_{max}$ is

$$Q_R = -\frac{|A||V_r|^2}{|B|} \sin(β - α) \quad (C.22)$$
APPENDIX-D

This section presents the data and single line diagram for IEEE-12, 33 and 69 bus RDS which are taken from [Das et al (1994)], [Venkatesh and Ranjan (2006)] and [Srinivas Rao (2010)] respectively. These test systems are used in the third strategy of load shedding described in the fifth chapter of this thesis.

D.1 DATA AND SINGLE LINE DIAGRAM OF IEEE 12-BUS RDS

Table D.1 Line data of IEEE 12-bus RDS

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<th>Branch no.</th>
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<th>X(ohms)</th>
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Table D.2 Load data of IEEE 12-bus RDS

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D.2 DATA AND SINGLE LINE DIAGRAM OF IEEE 33-BUS RDS

Table D.3 Line data of IEEE 33-bus RDS

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Fig. D.2 Single line diagram of IEEE 33-bus RDS

Table D.4 Load data of IEEE 33-bus RDS

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D.3 DATA AND SINGLE LINE DIAGRAM OF IEEE 69-BUS RDS

![Diagram of IEEE 69-BUS RDS](image)

Table D.5 Line and load data of IEEE 69- bus RDS

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