Modeling of Load During and After System Faults Based on Actual Field Data

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***Abstract* — Appropriately modeling load characteristics is important for power system analysis, in particular for voltage instability phenomena. Load modeling is becoming ever more important with the increasing penetration of power electronic based loads. In order to improve the process and accuracy of power system planning and to be able to make rational and economical decisions based on studies, appropriate load models for planning studies are critical. Thus, to improve load modeling, a study based on actual field data was carried out and is described in this paper.**

***Index Terms*—Load Modeling, Load Characteristics, Voltage Instability, Power System Dynamic Performance**

I. INTRODUCTION

In an environment of deregulation, investment for new facilities is severely limited due to economical reasons, thus power systems are being forced to be heavily loaded. In addition, older generators in urban areas are being decommissioned to save the high operation and maintenance costs. As a consequence, voltage instability problems are attracting more and more attention in power system operation, planning, and control. The appropriate and accurate modeling of load is critical in the evaluation of voltage stability in order to acquire practical solutions with respect to economics, reliability, security, etc.

There are various kind of loads in power systems, such as induction motors, large rectifiers, lighting, HVAC, TVs, PC, inverter-based electric heating, etc. The load characteristics at substation, which is typically the point where loads are modeled in power system planning load flow and stability studies, should reflect the aggregate effect of all of such loads connected to that substation [1,2], which can represent a significant challenge.

The exact modeling of reactive power is also particularly challenging. The reactive power measured at substation is not the reactive power consumed by loads rather it is the “net” or “compensated” value that includes the reactive losses in the lines, the effect of shunt capacitors and the reactive consumption of the loads. The reactive losses in the lines and the reactive power of shunt capacitors are integrated and modeled a shunt capacitor in this paper. Thus, major items to be considered for the modeling of load are as follows:

1) Division of reactive power into “active power dependent” and “independent”
2) Proportion of dynamic loads
3) Volume of load tripped by temporary voltage sag
4) Dynamic load time constant

The followings are results of studies for these items.

II. LOAD MODELING

A. Classification of the Reactive Power Load

Figure 1 shows an illustration of load in a power system. As described above, typically the active power measured at substation is approximately same as the summation of the power consumed by load on the various feeders emanating out of the respective substation. On the other hand, the reactive power measured at the substation is different from the total reactive power of the loads, because there are typically a significant amount of shunt capacitors on the feeders or in the customer substations to compensate the reactive power consumed by the loads. The effect of reactive power would be underestimated if the measured reactive power at substation were defined as the reactive power of load. Thus it is necessary to evaluate the amount of reactive power in the system, in advance of modeling of loads for power system planning studies. The total reactive power generated by shunt capacitors can be calculated by surveying all of the facilities of the utility and customers for the target power system. This is a reasonable approach if the system under study is relatively small. It is, however, still a time and cost consuming task, and furthermore it would be difficult to survey large power system or future power system being planned.

To solve this problem, the reactive power from shunt capacitor should be estimated from the active and reactive power data measurable at a substation.

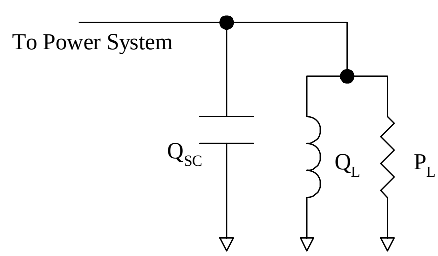


Figure 1. Illustration of Load in Power System on an Example Feeder

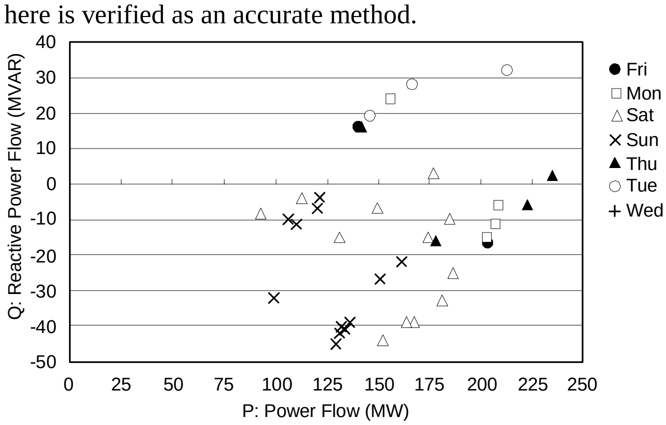
Figure 2(a) shows active power P and reactive power Q at a time of 15:00 in a summer season plotted in the P-Q plane. The relationship between P and Q cannot be easily observed by this data. Figure 2(b) shows the data after removing the load data of Saturdays, Sundays, and holidays because load configurations of those days are different from weekdays. It can be observed that the P-Q data are distributed on two lines.

$$Q = 0.6P_L - 70 \quad [MVAR] \tag{1}$$

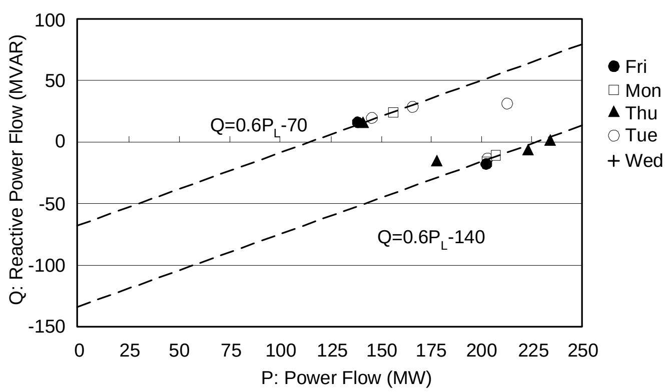
$$Q = 0.6P_L - 140 \quad [MVAR] \tag{2}$$

The reactive power consumed by load Q_L can be estimated as $Q_L = 0.6P_L$, and constant component of equations can be estimated as the reactive power generated by shunt capacitors.

It is observed that there is two operation modes of shunt capacitor values. One is 70 Mvar, and the other 140 Mvar. Since it is known that there are two system configurations for the power system served through the substation in summer season (weekdays and weekends/holidays), and total value of shunt capacitor in the system changed by the configuration. This is the reason why there are two groups of the data set. From this data, total capacity of the shunt capacitor can be estimated as 70 Mvar, and 140 Mvar respectively. As a point of verification of this method of analysis, a survey was performed as to the level of shunt capacitor compensation on the feeders of the substation under study. It was found to be 120 Mvar. Considering the embedded capacitor in small customers not able to be captured in the survey (in this case ≈ 20 Mvar), it is concluded that the proposed estimation method here is verified as an accurate method.



a) P & Q Flow at an Example Substation on Each Day of a Summer Season



b) P & Q Flow at an Example Substation on Each Weekday (Non-Holiday) of a Summer Season

Figure 2. Measured Data of P & Q at an Example Substation

B. Proportion of Dynamic Loads

The portion of load that has dynamic characteristics is very important to quantify for modeling and subsequent power system analysis. One of major loads that have significant dynamic characteristics is air conditioning load. Furthermore, air conditioners based on inverter technology are increasing in penetration year by year. Figure 3 shows distribution of load demand of the Kansai Electric Power (KEPCO) at a time of 15:00 on weekdays in the year 1999 to the temperature of the service area. The demand is constant at around 20 GW from air temperatures of 17 degrees to 23 degrees Celsius, and increases by 0.89 GW for an increase of each 1 degree. The estimated total demand for 35 degrees is 30.4 GW and the air conditioning load is 10.7 GW, a 35% of total demand. The air conditioner load has a constant power characteristic for the deviation of system voltage. There are various loads that have dynamic characteristics in addition to air conditioner load, such as induction motors, power electronics equipment used in industry, etc. The ratio of dynamic load is estimated to be 50 to 70% in the Kansai Electric power system. Note that here, we are focused on voltage stability just after system faults (i.e., 10 second time frame). Thus, the authors wish to note that the thermostatic effects of the loads [5] are too slow to be considered for this phenomenon of interest, consequently any thermostatic effects are categorized as static load here.

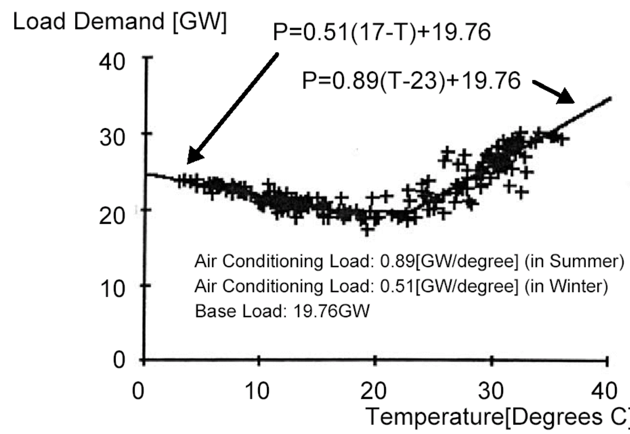


Figure 3. Distribution of Load Demand

C. Load Drop

Some types of loads are designed to trip for a voltage sag to protect it from mal-operation and/or damage. Some of the tripped loads are not restored after the voltage recovers. Figure 4 shows the relationship between tripped load and the lowest voltage during a voltage sag. The lowest voltage affects the volume of tripped load during fault. The load drop does not occur if the lowest voltage is higher than 0.85 pu. The load drop occurs if the lowest voltage becomes lower than 0.85 pu, and rapidly increase when the lowest voltage around 0.6 pu. The load drop, however, saturates after that and it does not increase over 30%.

The load drop changes case-by-case depending on the fault conditions. The result of any voltage stability studies would become optimistic (i.e., more stable) if load drop is considered. The load drop is not considered for typical voltage stability studies to avoid overly optimistic results and conclusions for the situation of misjudging the amount of load drop.

D. Other Considerable Parameters

The dynamic load response appears just after major system events, such as clearing system faults, with the active power P and reactive power Q changing with some time constant. The time constant is a function of such items as the severity of faults (i.e., the amount of voltage deviation), the operating condition of the power system, as well as the inherent responses of induction motors and other dynamic loads. Figure 5 shows the distribution of time constants calculated for 418 cases of measured faults over a time period of 10 years. As shown in Figure 5, the most frequent time constant is around 4 cycles (70 ms). Generally speaking, the time constant is short for small disturbance and long for severe faults.

For voltage stability studies, the time constants for active power and reactive power Tp, Tq are set to approximately 10 cycles (170 ms). This is to emphasize that severe fault conditions should be considered.

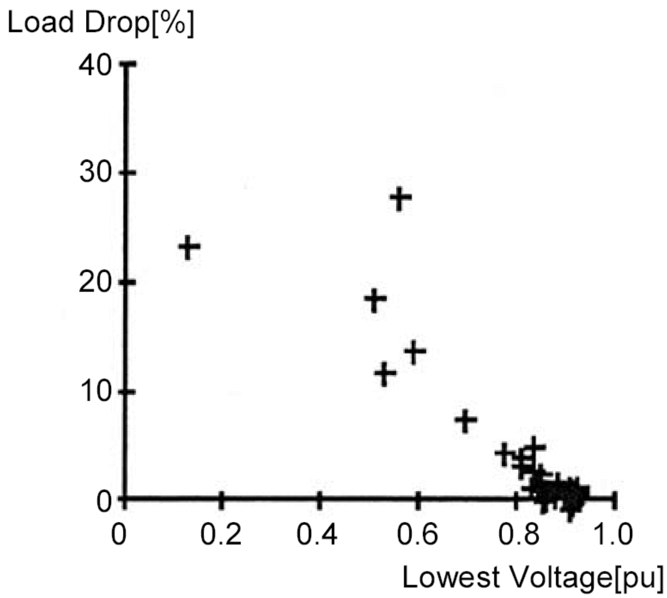


Figure 4. Measured Data of Load Drop by Faults

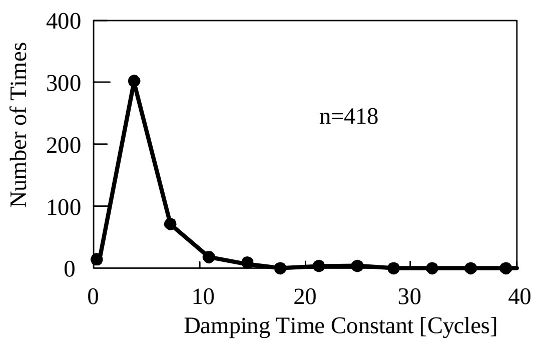


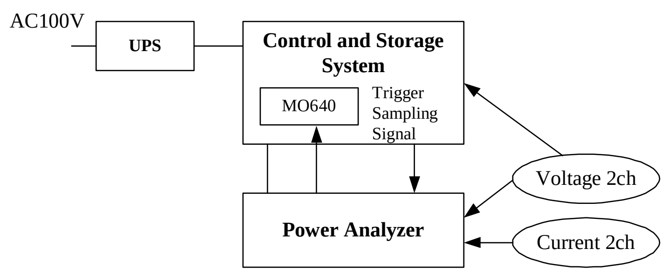
Figure 5. Distribution of Time Constants Calculated for 418 Cases of Measured Faults Over a Time Period of 10 years

III. The Measurement of Loads

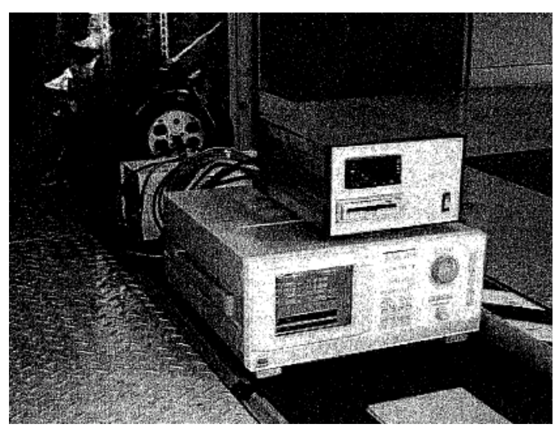
A. Measuring System for Power Characteristics

For load testing, the system voltage must be changed to acquire load characteristics with respect to voltage deviations. It is, however impossible to change the supply voltage of an actual power system without disturbing service to customer's connected equipment. To solve this problem, measured active and reactive power during and after system faults are surveyed in this study. Figure 6(a) shows the configuration of the measuring system. It consists of a power analyzer and a control and storage system that generates a triggering signal by sensing system voltage with data storage of the recorded events in a magno-optic disk media (MO), and an uninterruptible power supply (UPS). The UPS is essential since this system is expected to operate under situations with potentially large voltage deviations.

Two phases of voltage and current on the 6.6 kV side of 77 kV/6.6 kV transformers (typical of load substation transformers in the Kansai Electric system) are measured with a sampling frequency of 3 kHz. The event data, including the data before the trigger signal is generated, are stored for each event. Once a monitored voltage of the system drops below a pre-set threshold value, the trigger signal generating system generates a trigger signal and sends it to a multi-meter, and the multi-meter temporarily stores the event data. The stored data is sent to the control and storage system, described previously, and stored in the MO. Active power P, and reactive power Q, are calculated with the stored voltage and current data, and the calculated P and Q are also stored in MO. Figure 6(a) and 6(b) shows the concept and photograph of the system, respectively. This type of system is installed in several substations in the Kansai Electric power system. The storage data in the MO are gathered periodically by operating crews of KEPCO.



a) The Configuration of Measurement System



b) Front View of Measurement System

Figure 6. The Measurement System for Load Modeling

Figure 7 shows an example of the P, Q behavior for a voltage sag event. The voltage decreases to 0.87 pu, due to a fault in the upper trunk of the power system. The active power P decreases during fault. Following the fault, the P increases to larger than that before the fault, indicating that the load has significant dynamic characteristics.

The behavior of the load during and after a fault could be understood easier by plotting the data on a P-V plane instead of time domain charts. Figure 8(a) shows a time domain chart and Figure 8(b) shows a P-V plane plotting. An interesting observation was made on this one set of the measured data. The P-V points vary on a P-V characteristics curve before fault, and after clearing the fault, as indicated in the figure. However, it moved to another P-V characteristic curve during fault. The operating points are located to the lower side of the characteristics curve, and the point were moving to a lower voltage point, step by step. It was observed in this set of measurements that voltage instability occurred during the fault when viewing the power and voltage in the P-V plane. Fortunately, for this measured fault, the voltage instability condition during the relatively short duration of the fault was mitigated by its clearing. Then the operation point returned to original curve, and the voltage becomes stable again.

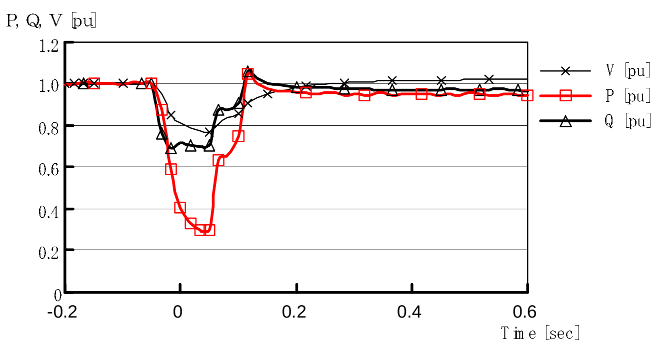
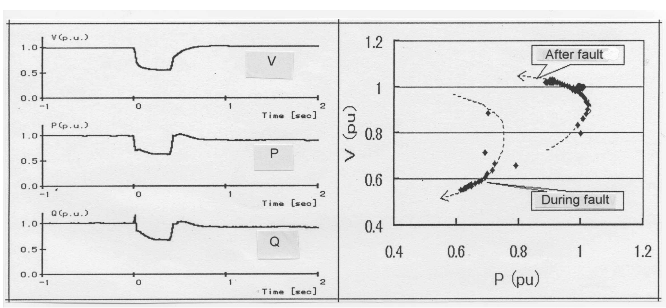


Figure 7. Measured Results of P, Q, and V in a Substation



a) Time Domain Chart b) P-V Plane Chart

Figure 8. An Example of Measured Load Data

IV. Load Modeling

A. Exponential Load Modeling

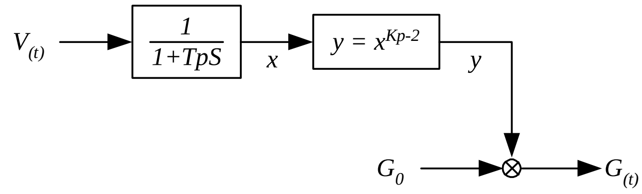
A number of load models have been advocated for dynamic performance analysis [3, 4, 5, 6, 7]. Equations (3) and (4) are for a widely used exponential load model. Figure 9(a) and 9(b) shows the block diagram of equations (3) and (4). This load model is typically used to analysis the general phenomena related to load dynamics

$$P_{(t)} = \frac{1}{1+T_pS} V_{(t)}^{Kp} \quad (3)$$

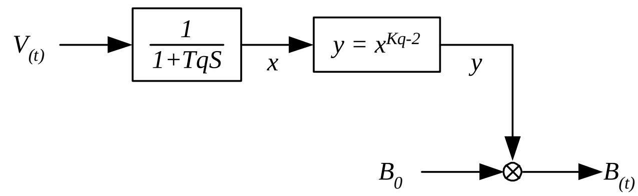
$$Q_{(t)} = \frac{1}{1+T_qS} V_{(t)}^{Kq} \quad (4)$$

where: $P_{(t)} = \frac{P}{P_0}$, $Q_{(t)} = \frac{Q}{Q_0}$, $V_{(t)} = \frac{V}{V_0}$

and P_0 is a rated voltage. P_0, Q_0 are the power consumed at rated voltage.



a) Power (P) Model of Load



b) Reactive Power (Q) Model of Load

Figure 9. Load Model

B. Suggested Model

Equations (5) to (10) are considered for the proposed load model [1], as described in Section II. Figure 10(a) and 10(b) are the block diagrams of equations (5) to (10). Each parameter is determined by the measured results of the loads, that is, actual characteristics of the loads connected to the target power system under study, as described in Section II.

$$P_{(t)} = [1 + Kp\{V_{(t)} - 1\}][(1 - Pdrop) + Pdyn\{G_{(t)}V_{(t)}{}^2 - 1\}] \quad (5)$$

$$Q_{(t)} = [1 + Kq\{V_{(t)} - 1\}][(1 - Qdrop) + Qdyn\{B_{(t)}V_{(t)}{}^2 - 1\}] \quad (6)$$

$$\frac{dG}{dt} = -\frac{1}{Tp}(G_0V_{(t)}{}^2 - 1) \quad (7)$$

$$G_0(t = 0) = 1 \quad (8)$$

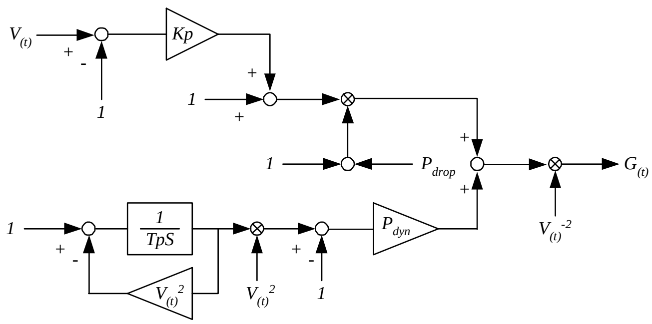
$$\frac{dB}{dt} = -\frac{1}{Tq}(B_0V_{(t)}{}^2 - 1) \quad (9)$$

$$B_0(t = 0) = 1 \quad (10)$$

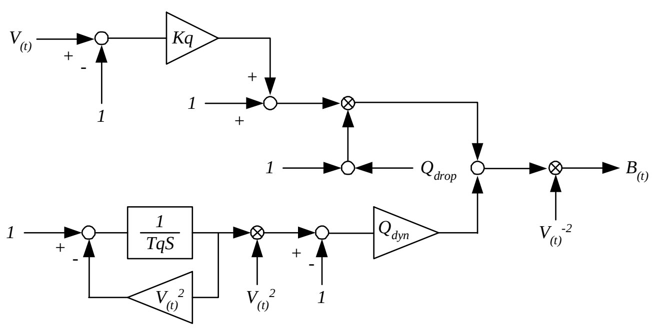
where :

Kp, Kq: Characteristic constants
Pdrop, Qdrop: Amount of the load drop [pu]
Pdyn, Qdyn: the percentage of dynamic loads [pu]
Tp, Tq: Damping time constant of conductance *G* and susceptance *B* after a fault

The representation of power and reactive power in the suggested load model includes static portions and dynamic portions of equations (5) and (6). The first term of equations (5) and (6) is for the static load model. It has slope characteristics for voltage changes and the load drop is considered. The characteristic constant *Kp* and *Kq* of the load are widely used values.



a) Power (P) Model of Load



b) Reactive Power (Q) Model of Load

Figure 10. Suggested Load Modeling Method

The second term of equations (5) and (6) is for the dynamic load model, where the percentage of the dynamic load is considered. *G(t), B(t)* in equations (5) and (6) are calculated by the conductance *G* and the susceptance *B* respectively with differential equations (7) to (10). These equations are derived from equation of motion of an induction motor, one of the main dynamic loads in power systems. Their factor appears only when voltage deviation occurs.

V. Application To Voltage Stability Analysis

Voltage stability analysis is performed to evaluate the classification of reactive power load shown in Section II, and to show an example of application of the suggested load model shown in Section IV.

A. Example 1 - Difference of Classification of Reactive Power Load

It was described in Section II that reactive power load model should be divided into two parts, namely, (a) consumed reactive power of the load and (b) shunt capacitors. In this example, the effect on power system by the classification of the reactive power load is verified. A sample system for voltage stability analysis is shown in Figure 11. Substation A and substation B connect to substation C with a 2-circuit transmission line with transformers at each termination. Each substation has its load aggregated and modeled on the respective buses as shown in Figure 11 on the secondary of a load substation transformer. Table 1 shows the sample parameters of the suggested load models used in simulation.

A P-V curve is calculated under the condition that 1 circuit of the transmission line in the sample system is outaged. Figure 12 shows the comparison of the case with the classification of the reactive power load and the case without it, as described in Section II. The vertical axis is the voltage at substation A. When the loads increase, the voltage at substation A tends to want to drop but is kept near rated voltage by the load tap changers of the transformers on the power system side. When voltage is kept at the rated value, the influence on the classification of the reactive power load is not significant, as is expected.

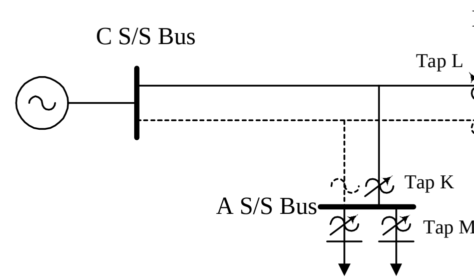


Figure 11. A Sample System for Voltage Stability Analysis

TABLE 1. THE SAMPLE PARAMETERS OF THE SUGGESTED LOAD

Kp	Kq	Pdrop [pu]	Qdrop [pu]	Pdyn [pu]	Qdyn [pu]	Tp [sec]	Tq [sec]
0.5	1.5	0	0	0.5	0.5	0.17	0.17

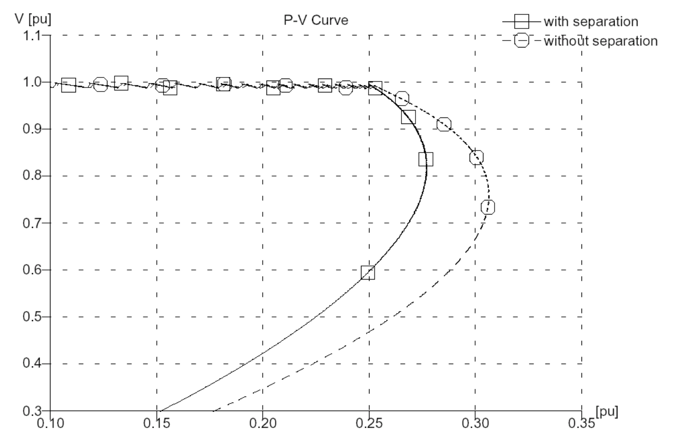


Figure 12. Comparison of the Classification of Reactive Power Load by P-V Curves

After reaching the limit of the load tap changer, the voltage on substation A begins to drop as the load continues to increase, and the influence on the classification of the load can be clearly identified. When the classification is considered, the limitation of power flow in the power system in terms of voltage stability reduces compared to without the classification. This is the result of the amount of the reactive power load considered with the characteristic constant Kq, as it increases by means of dividing the reactive power into that consumed by the load and the shunt capacitor for its compensation, thus the lagging reactive power increases under the voltage drop. In addition, it is assumed that the amount of reactive power load considered dynamics also increases and the dynamics have an effect.

The reactive power flow monitored in a substation is the difference between the consumed reactive power and the shunt capacitors used for compensation. When these two elements are not divided and modeled separately, the amount of reactive power modeled for the load tends to be relatively small (particularly in well-compensated systems), and it is observed that any study results in terms of voltage stability becomes more stable due to the “small” influence of load dynamics.

Thus this example shows that modeling of load based on the actual conditions of reactive power load (i.e., dividing the reactive load into the two portions) brings more accurate result in terms of voltage stability.

B. Example 2 - Application of Suggested Load Model

The suggested load model in Section IV is applied for voltage stability analysis in this example. The voltages at buses A and B drop significantly due to the increase of the transmission impedance when 1 circuit is opened under heavy power flow on the 2 circuit transmission line in the sample system shown in Figure 11.

Figure 13(a) through 13(e) shows the results of the voltage stability analysis under the condition of 1 circuit of the 2-circuit transmission line opening under heavy power flows. Figure 13(a) to 13(d) shows the voltages on the buses, load power and reactive power, and the value of the load tap changers of the transformers in substations A and B.

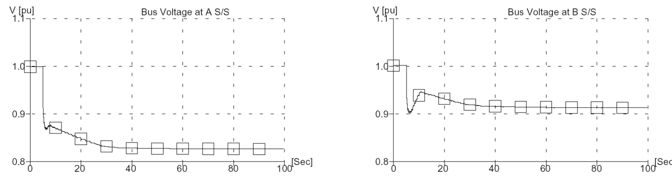
When one of the two circuits is opened, the heavy power flows on the remaining line causes the voltages at buses drop significantly. The voltages respond to the dynamics of the loads and the load tap changers of the transformers. When the load tap changers, Tap K and Tap L in Figure 11, reach their limits, the support of the voltages ceases. Since the load tap changers, Tap M and Tap N in Figure 11, support the voltages on the load sides, the consumed power of loads is maintained but the voltages on the buses of A and B substation drop.

Figure 13(e) shows the P-V curve at substation A. When one of the circuits is opened in the system of Figure 11, the operation point of substation A moves from the P-V curve with 2 circuits to the P-V curve with 1 circuit, as clearly shown in Figure 13. The load power increases and the voltage drops in terms of the dynamics of loads and load tap changers of the transformers serving the load. Voltage collapse does not occur in this case, as shown in Figure 13(a). However the final operation point is near the critical point of the P-V curve of 1 circuit, and this situation is considered to be at the limit of voltage stability.

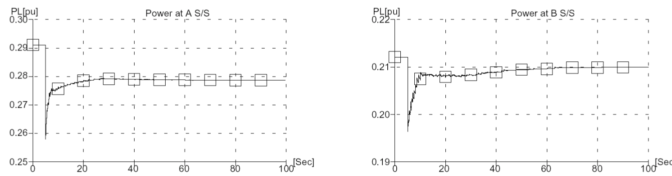
Thus, as this example illustrates, the actual load characteristics are critical and should be simulated and evaluated by considering dynamics of loads and load tap changers of transformers.

VI. Conclusion

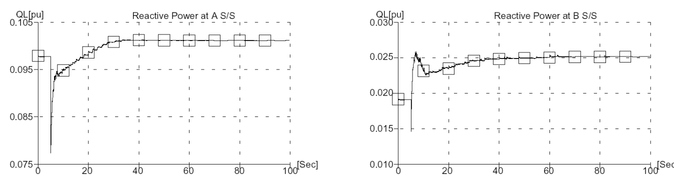
Appropriately modeling load characteristics is important for power system analysis, in particular for voltage instability phenomena. Load modeling is becoming ever more important with the increasing penetration of power electronic based loads. Thus, it is essential that modeling of load should be adequately considered by using the data of actual loads based on measurements. This paper addressed parameters to be considered for load modeling, such as: classification of reactive power loads; percentage of dynamic load; load tripping by voltage deviation; and time constant of dynamic loads. It is particularly important for the reactive power of loads to be divided into the consumed reactive power of loads and the shunt capacitor used for compensation. The consumed reactive power of loads contains the portion that has a dynamic and a static response to the system voltage change, while the shunt capacitors and line reactive losses have only a static response. In addition, this paper presents two examples on the impacts of the proposed load model on the influence of the results for voltage stability analysis.



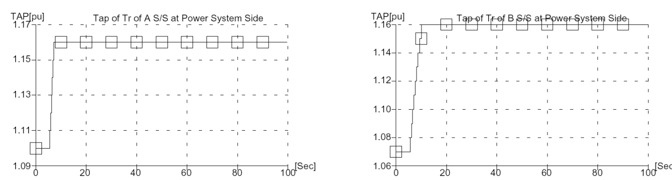
a) Bus Voltage in A substation (S/S) and B S/S



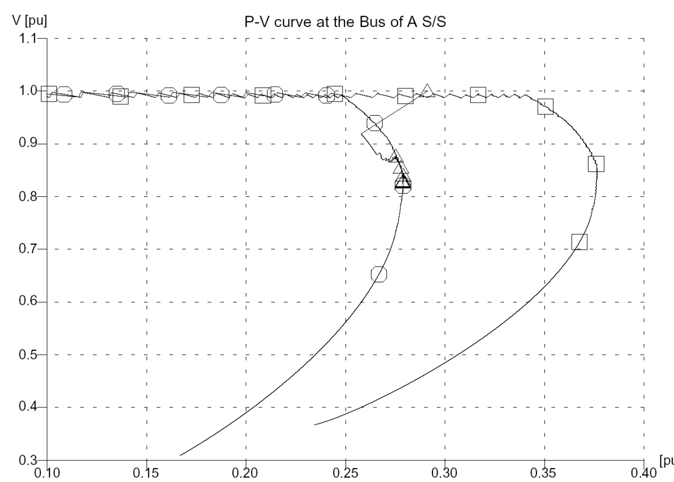
b) Power of Loads in A S/S and B S/S



c) Reactive Power of Loads in A S/S and B S/S



d) Status of Load Tap Changers of Transformers in A S/S and B S/S



e) Power – Voltage Curves in A S/S

○ In case of 1 circuit operation □ In case of 2-circuit operation

Δ P-V Locus Results of Voltage Stability

Figure 13. An Example of Results for Voltage Stability Analysis Using the Suggested Load Model

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VIII. Biographies

Katsuyuki Tomiyama is a senior researcher at the Technical Research Center of the Kansai Electric Power Company, Osaka, Japan. He joined KEPCO in 1963. He received the B.S.E.E. degree from Himeji Institute of Technology, Hyogo, Japan in 1971 and Ph.D. in Electrical Engineering from Kyoto University in 2000. Present responsibilities include the analysis and planning of the KEPCO transmission system and the operation of the Advanced Power System Analyzer. Dr. Tomiyama is a member of IEE of Japan.

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