

Effect of Different Load Models on Rotor Angle Stability

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Abstract— This paper describes the rotor angle stability of the system with different load models. The system was analyzed with the loads as constant impedance, constant current, constant power, and a specific combination of constant power with constant impedance. The system used in this paper being modeled in MATLAB/SIMULINK takes in to account detailed dynamic models of the generators. The results are the critical clearing time (CCT) for a specific line, with a three phase fault at a particular location. For the analyzed example, the lowest critical clearing time (CCT) was observed with constant power kind of loads.

Key words—Rotor Angle Stability, Load Models, and CCT.

I. INTRODUCTION

Rotor angle stability is the ability of the system to remain in synchronism after perturbing to some disturbance [1]. Remaining in synchronism means all the generators electromagnetic torque is exactly balanced by the mechanical torque. If in some generator the balance between the electromagnetic and mechanical torque is disturbed, due to disturbances in the system, then this will lead to oscillations in the rotor angle. Rotor angle stability is further classified in to small disturbance angle stability and large disturbance angle stability.

Small-disturbance or small-signal angle stability: It is the ability of the system to remain in synchronism when subjected to small disturbances. If a disturbance is small enough so that the nonlinear power system can be approximated as linear system, then the study of the rotor angle stability of that particular system is called as small-disturbance angle stability analysis. Small disturbances can be small load changes like switching on or off of small loads, line tripping, small generator tripping etc. Due to small disturbances there can be two types of instability: non-oscillatory instability and oscillatory instability. In non-oscillatory instability the rotor angle of a generator keeps on increasing due to small disturbance and in case of oscillatory instability the rotor angle oscillates with increasing magnitude.

Large-disturbance angle or transient stability: It is the ability of the system to remain in synchronism when subjected to large disturbances. Large disturbances can be faults, switching on or off of large loads, Large generator tripping etc. The time domain of interest in case of large-disturbances as well as small-disturbance angle stability is anywhere between 0.1 to 10 s.

The effects of load modeling on rotor angle stability especially

transient stability have been studied in several researches. From the obtained results it is concluded that the system loads and the way they are modeled might considerably affect transient stability of the system. It means that the results obtained using constant-power, constant-current and constant-impedance load models are different from each other.

In [2] the effects of amount of load and distance between load and fault location on CCT are studied. Simulations are performed on the IEEE 39 bus test system. In each case the load of a single bus is changed and the effect of this variation of transient stability of the system is studied by applying faults on different buses of the system. In this reference a simplified method to modify the reduced admittance matrix after load changes is proposed.

In this paper an extensive study of the effect of load modeling on transient stability of the system is performed and some of the results are presented. In the following section of the paper major load modeling methods, which are extensively using in the simulation studies are introduced. In the third section of the paper load representation for stability studies is described. In the fourth section of the paper system modeling used for the simulation is described. In the fifth section the results of simulations are shown and analyzed. In the last section of the paper conclusions are presented.

II. LOAD MODELING

Stable operation of a power system depends on the ability to continuously match the electrical output of generating units to the electrical load on the system. The modeling of loads is complicated because a typical load bus in stability studies is composed of a large number of devices such as fluorescent and incandescent lamps, heaters, motors, compressors and so on [3]. The exact composition of load estimation is difficult. The load models are traditionally classified in to two categories static models and dynamic models.

A. Static Load Models

A static load model expresses the characteristics of the load at any instant of time as algebraic functions of the bus voltage magnitude and frequency at that instant of time [4]. The active power component P and reactive power component Q are considered separately. Traditionally, the voltage dependency of load characteristics has been represented by the exponential model:

$$\begin{aligned} P_L &= P_{L0} \cdot (\bar{V})^a \\ Q_L &= Q_{L0} (\bar{V})^b \end{aligned} \quad (1)$$

Where,

$$\bar{V} = \frac{V}{V_0}$$

Where P_L and Q_L are active and reactive power components of the load when the bus voltage magnitude is V . The subscript '0' indicates the values of the respective variables at the initial operating condition.

The parameters of this model are the exponents a and b . With these exponents equal to 0, 1 or 2, the model represents constant power, constant current, or constant impedance characteristics, respectively.

An alternative model which has been widely used to represent the voltage dependency is the **polynomial model**,

$$\begin{aligned} P_L &= P_{L0} (a_1 + a_2 \bar{V} + a_3 \bar{V}^2) \\ Q_L &= Q_{L0} (b_1 + b_2 \bar{V} + b_3 \bar{V}^2) \end{aligned} \quad (2)$$

This model is commonly referred to as ZIP model, as it is composed of constant Impedance [Z], constant current [I], and constant power [P] components [4].

In addition to voltage dependency, the effect of frequency variations on the active and reactive components of loads is accounted as follows:

$$\begin{aligned} P_L &= P_{L0} \{a_1 + a_2 \bar{V} + a_3 \bar{V}^2\} \left[1 + k_{pf} \frac{\nabla f}{f_0} \right] \\ Q_L &= Q_{L0} \{b_1 + b_2 \bar{V} + b_3 \bar{V}^2\} \left[1 - k_{qf} \frac{\nabla f}{f_0} \right] \end{aligned}$$

Where,

k_{pf} , k_{qf} = frequency sensitivity coefficients

∇f = deviation in bus frequency in Hz

f_0 = nominal frequency in Hz.

B. Dynamic Load Models

A Dynamic load model expresses the active and reactive powers at any instants of time as functions of the voltage magnitude and frequency at past instants of time and, usually, including the present instant. In other words these models account for dynamic characteristics of loads. The most attributable dynamic aspect of loads comes from motors. Studies of inter area oscillations, voltage stability, and long term stability often require load dynamic to be modeled. Difference or differential equations can be used to represent such models [5].

C. Composite Load Models

The composite load model can be used to include the influence of various components. It consists of a static load and an aggregate induction motor load [5]

III. LOAD REPRESENTATION FOR STABILITY STUDIES

The modeling equations of power system are in the form of a set of differential-algebraic equations (DAEs) given by [8]

$$\dot{x} = f(x, \bar{V}, u) \quad (3)$$

$$Y_{BUS} \bar{V} = \bar{I}(x, \bar{V}, S_L) \quad (4)$$

Where, x represents the state variables.

u represents input vector

In Eq.(4), the vector of injected bus currents, \bar{I} in general, represents a combination of generators source currents, and load currents, \bar{I}_L . Where \bar{I}_L is related to load power, S_L and bus voltage, \bar{V} as given by the following expression.

$$\bar{I}_L = -\left(\frac{S_L}{\bar{V}}\right)^* \quad (5)$$

Loads are modeled as aggregate static loads, employing polynomial representation. This method of modeling loads is given in Eq. (2). The coefficients a_1 , a_2 and a_3 are the fractions of the constant power, constant current and constant impedance components in the active load powers, respectively. Similarly, the coefficients b_1 , b_2 and b_3 are defined for reactive load powers. While selecting these fractions, it should be noted that

$$a_1 + a_2 + a_3 = 1$$

$$b_1 + b_2 + b_3 = 1$$

From Eq. (2) the load power is given by

$$S_L = P_L + jQ_L$$

If both active and reactive powers are modeled as constant impedance kind of loads i.e., by setting $a_1=a_2=0$ and $a_3=1$, $b_1=b_2=0$ and $b_3=1$ then the load admittance is given by

$$Y_L = \left(\frac{P_{L0} - jQ_{L0}}{V_0^2}\right)$$

Now, the load admittance Y_L can be absorbed into Y_{BUS} , to make the algebraic Eq.(4) linear. Modeling of active and /or reactive components as constant power/ current type (i.e., by having a_1 and /or a_2 , b_1 and /or b_2 non-zero), makes the Eq. (4) non-linear. The load at a bus is represented by an equivalent as shown in Fig 1. In the Fig 1, the load admittance Y_L has been absorbed into Y_{BUS} .

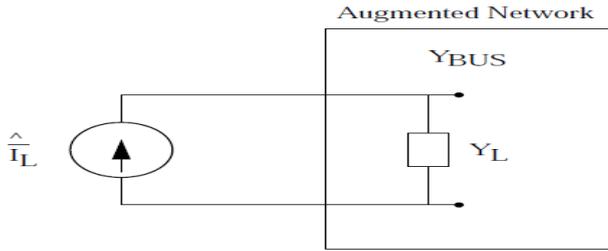


Fig. 1. Equivalent circuit of load.

Modification of constant power type load characteristics

It is found that, when the active load power component is represented as constant power type, the programme encounters numerical convergence problem. This is true especially when there is a severe dip in the bus voltage. This problem is overcome by adopting the following characteristic

When the voltage magnitude at i^{th} load bus drops below V_c ($=0.6$), change the active load power component at that bus as

$$P_{Li} = P_{Loi} \left(\frac{V_i}{V_c} \right)^2$$

In general, the types of load models used are summarized in Fig 2.

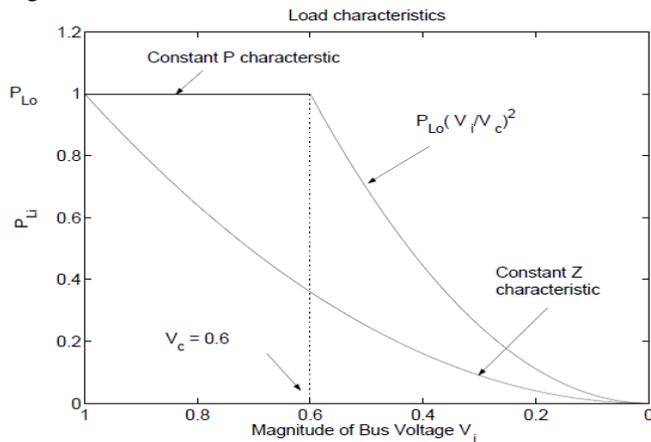


Fig 2: Summary of load models.

IV. SYSTEM MODELING

The single line diagram of a 4 machine power system is shown in Fig 3. The system details are adopted from [6]. The generator connected to bus 3 is considered as the slack bus. The load models as discussed in the previous section are considered on the system load buses. The 3 phase synchronous machines are modeled in the rotor reference frame. The representation of the rotor circuits is normally referred to as 2.2 model [6]. The transmission network mainly consists of transmission lines and transformers.

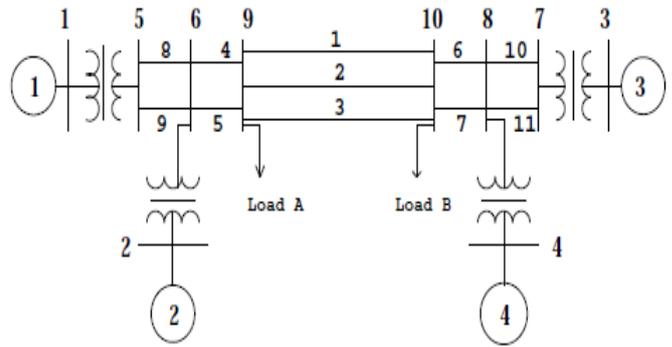


Fig 3: Four machine power system.

Since the time constants of these elements are relatively small compared to the mechanical time constants, the network transients are neglected and the network is assumed to be in sinusoidal steady state. Transmission lines and transformers are modeled as a nominal π circuit [7].

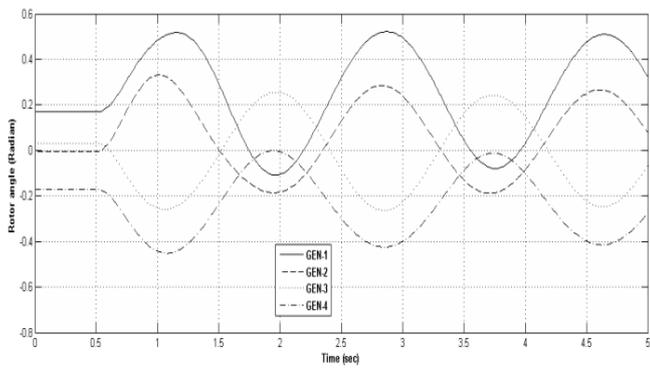
V. SIMULATION STUDIES

Transient stability analysis on the 4 machine system introduced in the previous section is performed in four cases of constant-power, constant-current constant-impedance loads and Hybrid loads. Transient stability analysis of the system is evaluated by power angles of the system generators following a major disturbance. To model a great disturbance, a three phase fault is simulated on any bus of the system. A 3 phase bolted fault is applied at $t=0.5$ s at bus 9. This fault is cleared by tripping line 1 (9-10). Fig 4 and Fig 5 shows the evolution of main variables like rotor angle of the generators and voltages of the generator buses for the following load models: constant impedance, constant current, constant power and a hybrid model (60% as constant power and 40% as constant impedance). The case with loads modeled as a constant power has the largest amplitudes of the oscillations for the variables under study.

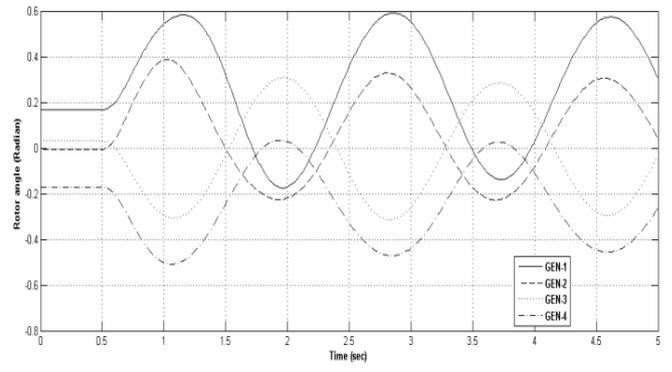
TABLE I shows the critical clearing times obtained with the mentioned load models. For the analyzed cases, the lowest critical clearing times were obtained with the constant power model, the highest values were obtained with the constant impedance model, and the other two models have intermediate results.

TABLE I. CRITICAL CLEARING TIMES WITH DIFFERENT LOAD MODELS

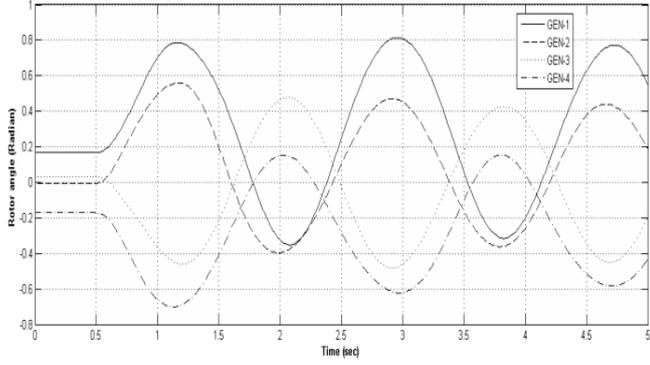
Load Model	Time (sec.)
Constant Impedance	0.363
Constant Current	0.29
Constant Power	0.172
Hybrid : 60 % as constant power 40 % as constant impedance	0.27



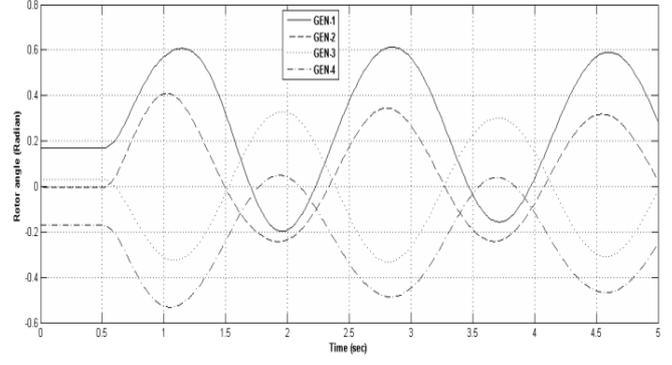
a) Constant Impedance Load



b) Constant Current Load

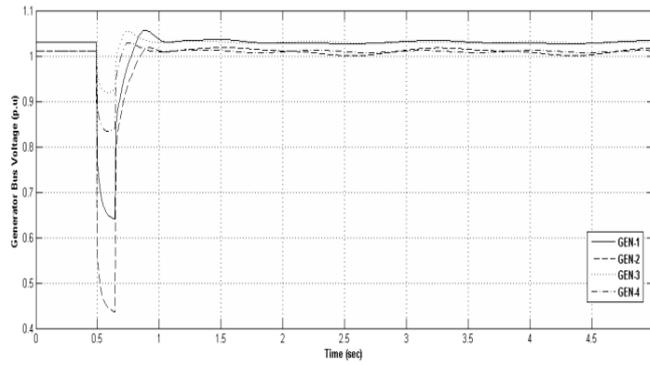


c) Constant Power Load

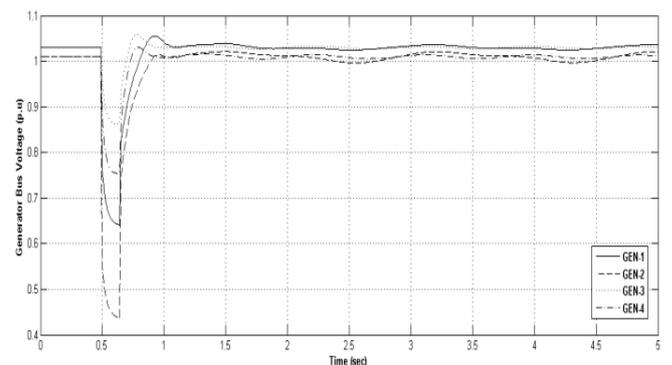


d) Hybrid load (60% as constant power and 40% as constant impedance)

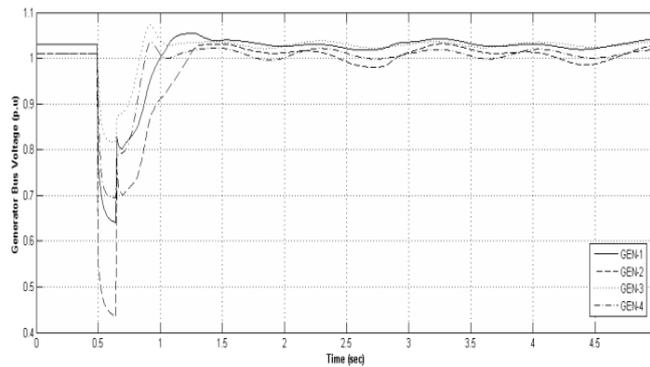
Fig 4. Generator Rotor Angles for Different Load Models



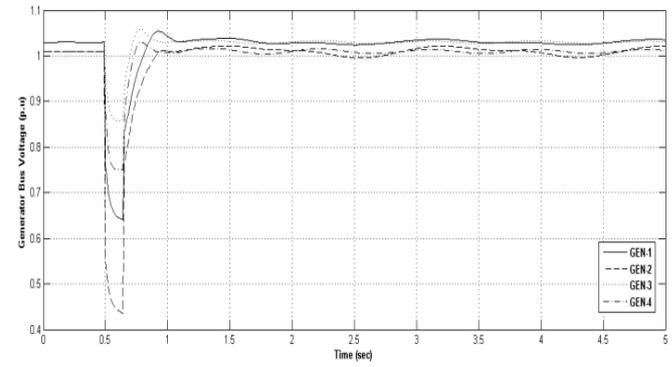
a) Constant Impedance Load



b) Constant Current Load



c) Constant Power Load



d) Hybrid load (60% as constant power and 40% as constant impedance)

Fig 5. Generator Bus Voltages for Different Load Models

and 7 shows the Generator-1 Rotor angle and its bus voltage respectively, with different load models for a particular fault clearing time. It clearly shows that with constant power kind of load, generator rotor angle becomes out of step (unstable) and with constant impedance kind of loads the amplitude of the oscillations has reduced. The generator bus voltage is settling to steady state value quickly with constant impedance kind of load where as it is oscillating with constant power kind of load. Generally all motor loads are modeled as constant power kind of loads by neglecting the dynamics of the motor.

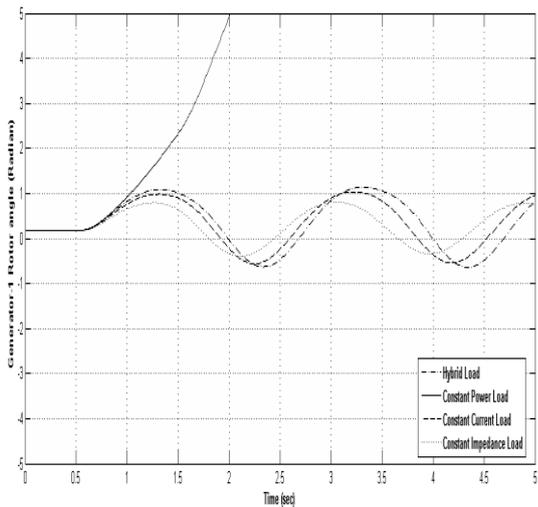


Fig 6: Generator-1 Rotor angle with different load models

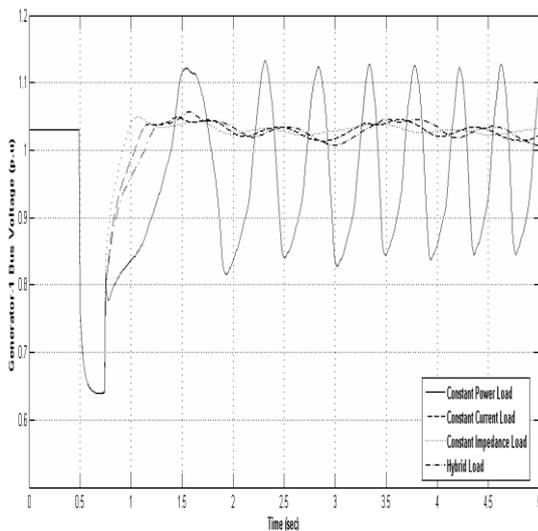


Fig 7: Generator-1 Bus Voltage with different load models

From the results of simulations presented the following conclusions are made. Load model may considerably affect transient stability of the system. It means that the results of constant power, constant current and constant impedance

loads are different from each other.

- Transient stability results obtained from small network cannot be generalized for all real large scale systems.
- Accurate load modeling in transient stability analysis is too complicated and it needs some simplifications. All the induction motors connected to a bus bar may be modeled as a single motor, to reduce the complexity of load modeling to some extent.

In this paper only static load model has considered.

VI. CONCLUSION

In this paper, effect of load modeling on power system transient stability studies was studied. For the analyzed example, the lowest critical clearing times were obtained with constant power model for loads. The highest critical clearing times were obtained with constant impedance model for loads.

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