Load Models and Impact on Static Voltage Stability Margins

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Abstract: Power systems with environmental and economic constraints are prone to voltage instability as operating under stressed conditions. Load characteristics and dynamics of power system components acquire an essential role in the phenomena of voltage instability and voltage collapse. Therefore, voltage stability analysis requires better knowledge and modeling of the power system components for accurate status of voltage stability margins at current operating conditions. In this paper, a brief review of load models developed so far utilized for power flow and stability analysis is given. The effect of load types on static voltage stability in view of line stability indices has been investigated using polynomial load model. Load flow results of PSAT for IEEE 30 bus system and MATLAB programming is done to obtain the results. The results show that constant power types of loads have minimum stability margins as expected.

Keywords: ***Voltage instability, Voltage collapse, Load characteristics, Load models, Line stability indices***.

I. INTRODUCTION

The environmental considerations, restructuring, deregulation, and high installation price of new transmission lines drive the power grid to function under stressed state. A small fluctuation at this condition may lead to blackouts in wide area of power system [1- 3]. The outcome of these blackouts includes significant fiscal losses and irreparable social costs. Case-studies have shown that the cause may be gradual load increase, large sudden tripping of generator or heavily loaded transmission line. The load is transferred to the adjacent lines resulting in overloading and reduction of voltages at the load ends. The action of AVRs of generators and ULTC transformers tries to restore the voltages and hence loads. This leads to increase in line losses and further voltage drops. The generator reactive power output increases and eventually hit its limits transferring the share to nearby generator. Thus, cascade tripping of overloaded generators and lines result in a major blackout [4-6]. Thus, voltage stability analysis is imperative for secure and reliable operation of power systems.

According to Cutsem T. V. and Vournas C. “voltage instability stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system”[3]. Loads and their characteristics at low voltage are one of the major reasons of voltage instability (VI). Therefore, VI is also termed as load instability to highlight the meticulous contribution of loads to this phenomenon. This contribution has been addressed in [7] - [12]. Many indices have been formulated so far to evaluate voltage stability state in terms of bus, line and overall stability indices [13]-[18].

The motive of this work is to investigate the impact of load types (Constant power, constant current and constant impedance) on voltage stability margins in terms of line stability indices. Gist of load models utilized for static and dynamic voltage stability analysis are described in section II. Section III elaborates conventional and new line stability indices formulation. Impact of load types on these line stability indices has been simulated in section IV. The last section concludes the results and analysis of investigation.

II. LOAD TYPES AND MODELING

An electric load may be any device connected in a power system that absorbs power. Therefore, load includes major load as connected load devices and transformers, lines, regulators, compensating devices, capacitors along with all the equipments connected at generation, transmission and distribution levels. The variation of load power (active and reactive), torque or current with changes in voltage and frequency are called as its load characteristics. Various load characteristics can be expressed as mathematical expressions depending on their behavior with respect to voltage and frequency. Loads having changing characteristics with voltage and time are called as dynamic loads. Load modeling implies to find basic mathematical expressions with fairly accurate load characteristics. As the frequency remains almost constant, voltage dependence is considered of primary concern in voltage stability studies and generally expressed by equations (1) and (2).

$$P = P(V) \qquad (1)$$

$$Q = Q(V) \qquad (2)$$

The most general classification of load models based on their characteristics and studies involved is as follows:

- Static Load Models
- Dynamic Load Models
- Composite Load Models

A. *Static Load Models*: This model is a specific function of voltage that remains same under all conditions. It is basically representation of static loads (resistive and lighting) or an approximation of dynamic loads (induction motor load). Most widely used load models are[2], [3]:

(i) Exponential model: In this model load powers are expressed as an exponential function given by equations (3) and (4).

$$P = P_o\left(\frac{V}{V_o}\right)^{\alpha} \qquad (3)$$

$$Q = Q_o\left(\frac{V}{V_o}\right)^{\beta} \qquad (4)$$

Where

P_o, Q_o, V_o : Active power, reactive power and voltage initially

α,β: Exponents depending on load characteristics

Three major types of loads for the following values of exponents are:

- Constant impedance(Z); $\alpha = \beta = 2$
- Constant current (I); $\alpha = \beta = 1$
- Constant power (P); $\alpha = \beta = 0$

The corresponding characteristics of constant impedance, constant current and constant power are shown in Fig. 1.

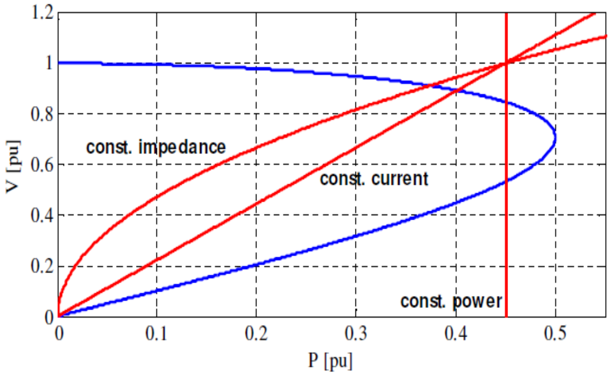

Figure 1: Load characteristics of various loads

Table 1 shows the exponent values for various types of loads.

Table 1: Exponent values for static characteristics

Load Type	α	β
Air conditioner	0.088 - 0.468	2.3 - 2.5
Heaters	2.0	0
Dishwasher	1.8	3.6
Cloths washer	0.08	1.6
Cloths dryer	2.0	3.6
Refrigerators	0.77	2.5
Televisions	2.0	5.1
Incandescent lights	1.55	0
Fluorescent lights	0.96	7.4
Industrial motors	0.07	0.5
Fan motors	0.08	1.6
Agricultural pumps	1.4	1.4
Arc furnaces	2.3	1.6

(ii) Polynomial/ZIP model: This model is widely in use for steady-state and dynamic studies. The power relations with the voltage magnitude in this model are expressed as equations (5) and (6).

$$P = P_o\left\{a_1\left(\frac{V}{V_o}\right)^2 + b_1\left(\frac{V}{V_o}\right) + c_1\right\} \qquad (5)$$

$$Q = Q_o\left\{a_2\left(\frac{V}{V_o}\right)^2 + b_2\left(\frac{V}{V_o}\right) + c_2\right\} \qquad (6)$$

Where $a_1, b_1 and c_1$ are the constant impedance, constant current and constant power coefficients of the total active power, respectively and $a_2, b_2 and c_2$ are the constant impedance, constant current and constant power coefficients of the total reactive power, respectively with the following conditions:

$$a_1 + b_1 + c_1 = 0; \quad a_2 + b_2 + c_2 = 0 \qquad (7)$$

***B. Dynamic Load Models*:** Studies involving transient and voltage stability requires dynamics of loads also to be included in the load models. These are of mainly two types:

(i) Induction Motor Model (IMM): The equivalent circuit of induction motor [2] as shown in the Fig. 2 is utilized as its dynamic model.

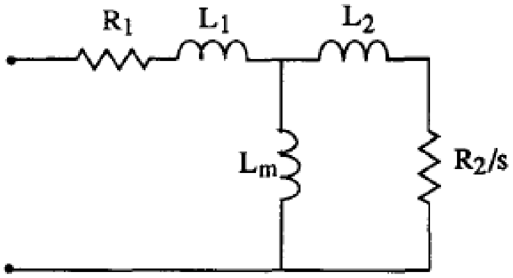

Figure 2: Equivalent circuit of induction motor for its dynamic model

Where:

R_1, R_2: Stator and rotor windings resistances respectively;
L_1, L_M, L_2: Stator, magnetizing and rotor windings inductances respectively.

(ii) Exponential Recovery Load Model (ERLM): The ERLM represents power responses to step disturbances of the voltage magnitude at the bus [7], [19]. This model is generally used for loads that slowly restore over a time period of several seconds to tens of minutes. Thus, ERL is also used to model discharge lamps, protective relays thermostatically controlled loads and on-load tap changers (OLTCs) which restore the nominal supply voltage after a disturbance.

C. Composite Load Models**:** Recent researches included combination of dynamic and static load models and accomplished that composite models give more accurate results [20] [21] [22].

The generally used composite models are as follows:

(i) ZIP+IM Model:
(ii) Complex Load Model (CLOD)
(iii) Western Electricity Coordinating Council (WECC) CLM

According to the study in [23], ZIP+IM Model is the most widely adopted model for dynamic stability studies. CLOD [24] represents a composite dynamic model of voltage dependent loads such as induction motors(large and small), discharge lighting, transformers with saturation effects, constant power and shunt capacitors etc. WECC-CLM is an interim composite load model containing static and dynamic parts (80% and 20% respectively) and implemented by WSCC [25]. It has been utilized in major industry simulation programs like Power-World Simulator and Siemens PTI PSSE.

III. LINE STABILITY INDICES AND FORMULATION

Line stability indices identify critical lines and are obtained from line flows of load flow analysis [26-29]. The stability criterion is based on either maximum power transfer through single line connected between two buses or existence of feasible receiving end voltage solution as shown in Fig. 3. These indices had been developed either by equating the Thevenin's impedance and load impedance or the discriminant of receiving end voltage equation to zero.

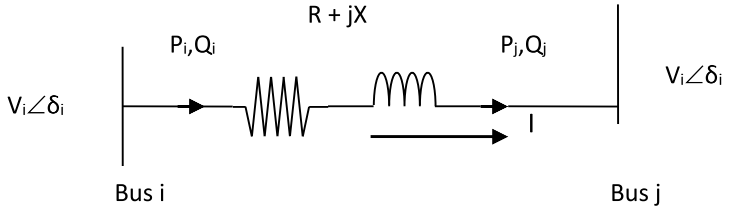

Figure 3: Line diagram of a transmission line

Imperative line stability indices:

- Line Stability Factor *LQP* [26]

This index developed by Mohamed et al. is shown by equation (8):

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(Q_j + \frac{P_i^2 X}{V_i^2}\right) \qquad (8)$$

- Line Stability Index L_{mn} [27]

The L_{mn} index proposed by Moghavvemi et al. is given by equation (9)

$$L_{mn} = \frac{4XQ_j}{[V_i \sin(\theta - \delta)]^2} \qquad (9)$$

- Fast voltage stability index *FVSI* [28]

For a transmission line, the FVSI proposed by Musirin et al. is calculated as:

$$FVSI = \frac{4Z^2 Q_j}{V_i^2} \qquad (10)$$

Where:

Z, R, X, Θ: Line parameters (impedance, resistance, reactance and impedance angle respectively
P_j , Q_j: Active and reactive powers at the receiving bus
P_i : Active power at the sending bus
V_i , V_j: Sending and receiving end bus voltages respectively
δ: Angle difference between V_i and V_j

These line indices should be less than unity for stable operation.

- Line collapse Proximity Index *LCPI* [29]

The formulation of line indices proposed in [26-28] have not considered the line charging reactance and the direction of active power flow with respect to reactive power flow. The index LCPI proposed by Tiwari R. et al has been derived from pie model and corresponding ABCD parameters of a two bus system as shown in Fig. 4.

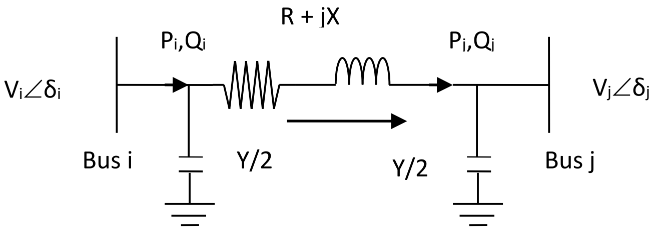

Figure 4: Line diagram of a transmission line considering capacitance

The relation in matrix form can be represented by equation (11).

$$\begin{bmatrix} V_i \\ I_i \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_j \\ I_j \end{bmatrix} \qquad (11)$$

The condition for voltage stability is obtained by equating the discriminant of quadratic in V_j. Thus, the expression obtained for the index in terms of ABCD parameters is given by equation (12).

$$LCPI = \frac{4A\cos\alpha\left(P_j B\cos\beta + Q_j B\sin\beta\right)}{(V_i\cos\delta)^2} \tag{12}$$

Where:

α, β: Phases of A and B respectively

δ: Phase difference between V_i and V_j

Voltage stability of the system is maintained till the index remains less than unity ($LCPI < 1$).

IV. SIMULATION RESULTS AND ANALYSIS

The effect of load types on line voltage stability margins has been investigate with PSAT [30] and IEEE 30 bus system. The line stability indices have been calculated with programming in MATLAB and load flow results of PSAT with different types of loads. The powers at the load buses are increased near to voltage collapse point and various line stability indices are calculated.

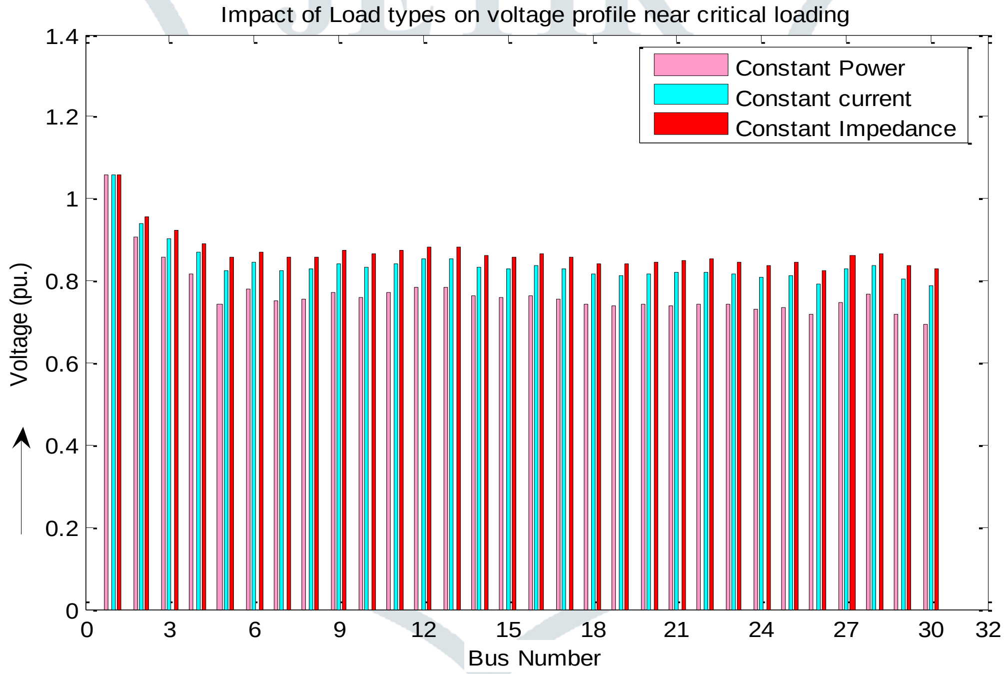

Figure 5: Voltage profiles for various types of loads

A. *Line Stability Factor LQP*

Bar plots for various line with different types of loads (Constant power, constant current and constant impedance) are shown in the Fig. … The lines become more stressed with constant power types of load as indicated and therefore stability margin decreases. The index value is maximum for the line 2. The pattern is almost same for all the lines having maximum value of index for constant power and minimum for constant impedance type of loads.

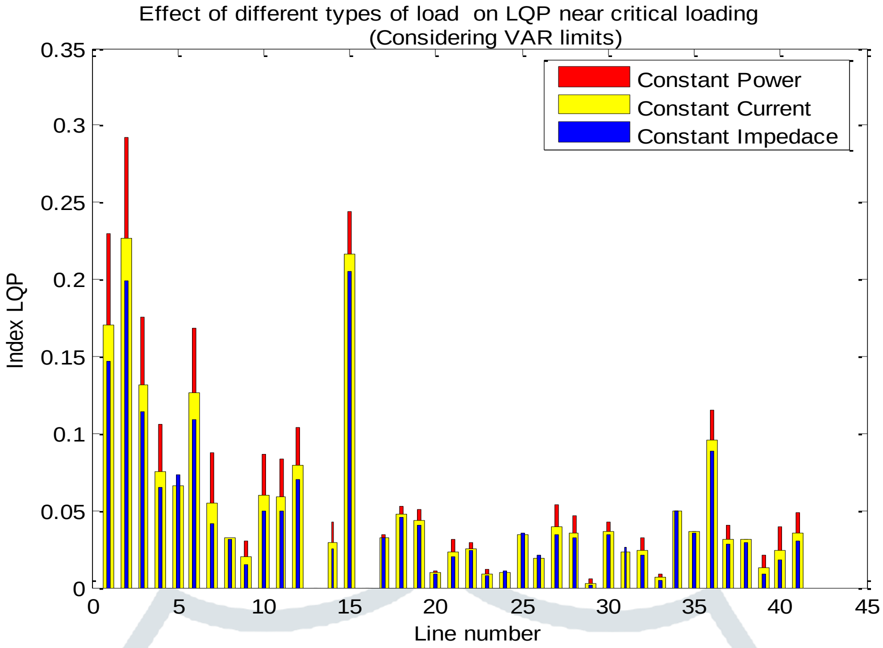

Figure 6: Impact of load types on the index *LQP*

B. *Line Stability Index L_{mn}*

The index L_{mn} has been calculated and shown in Fig. 7.

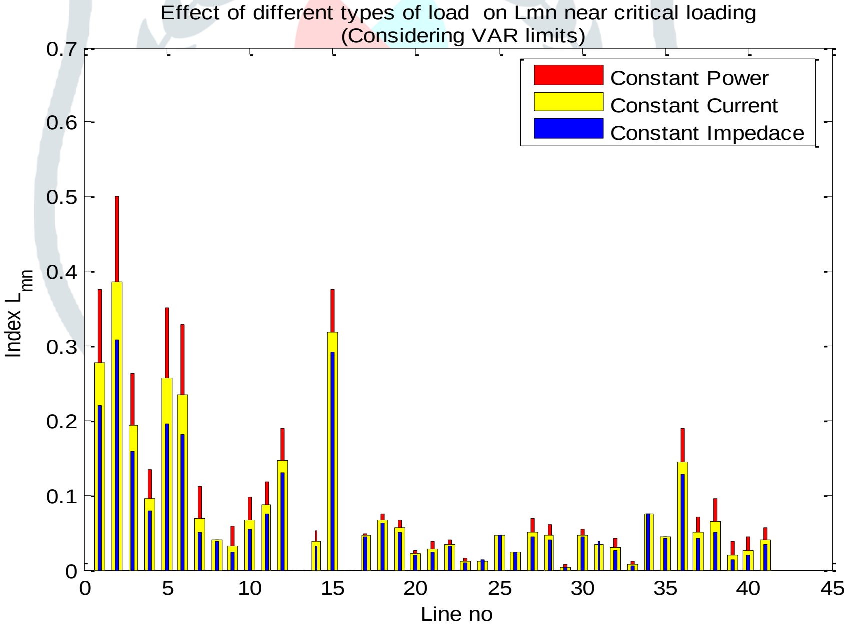

Figure 7: Impact of load types on the index L_{mn}

The results show that the line 2 is the most critical line as the index for this line has the maximum value.

C. Fast voltage stability index FVSI

The index FVSI is calculated for different loads and the results plotted are shown in Fig. 8.

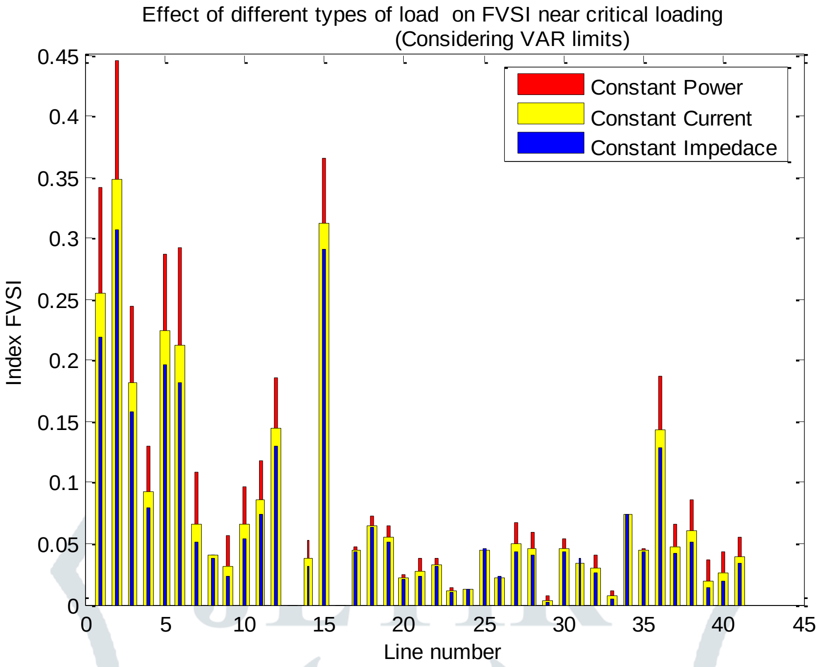

Figure 8: Impact of load types on the index FVSI

D. Line collapse Proximity Index LCPI

Fig. 9 shows the impact of load types on the index *LCPI*. The results are similar and indicate that the line 2 is the most critical.

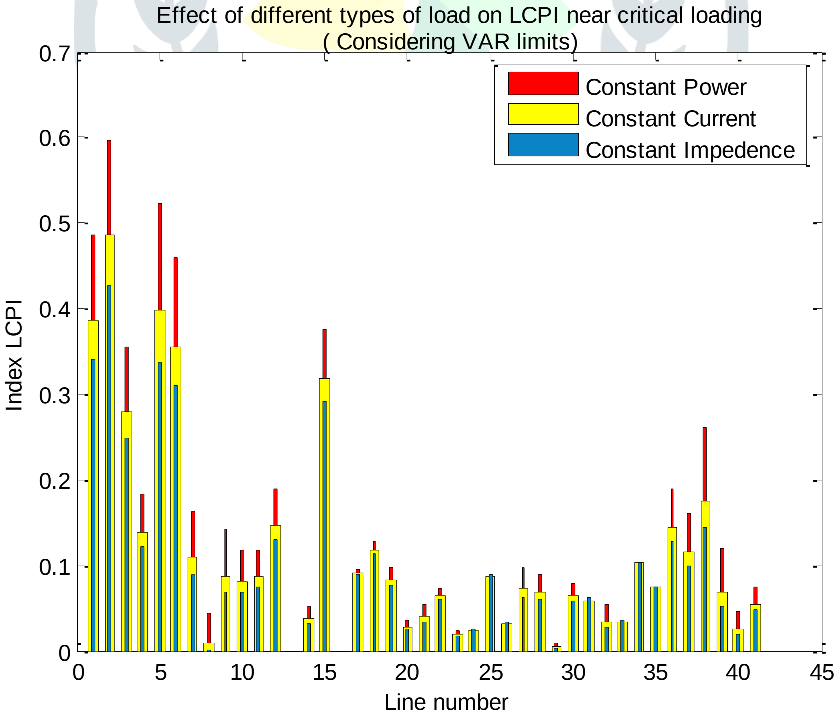

Figure 9: Impact of load types on the index *LCPI*

V. CONCLUSIONS

The various types of load models that are developed and employed for steady state and transient voltage stability are described. Static models are exponential and polynomial load models. These are used for steady state stability problems. Dynamic load models include induction motor model and exponential recovery load model. These models are used for dynamic analysis when the load characteristics changes with the change in system parameters (Voltage and frequency). Composite load models are the combination of static and dynamic load models. Line stability indices are formulated from the concepts of maximum power transfer through a line and feasible voltage solution of receiving end voltage. Simulation results deduce that constant power loads are the most critical type of loads as emphasized in various steady state stability studies. Various line stability indices are maximum (Near to 1) for constant power loads. Constant impedance types of loads are not critical to static voltage stability margins.

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