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Dynamic Voltage Stability Enhancement of a Microgrid with Static and Dynamic Loads Using Microgrid Voltage Stabilizer

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Abstract: *Voltage stability is a dynamic phenomenon and in order to tackle the voltage stability problem more realistically, dynamic representation of all power system components is necessary. The influence of load on dynamic stability is significant. In most studies, load representation of power systems are considered as constant power type but in real life there are different types of loads as industrial, agricultural and residential etc. Loads in a power system have to be represented realistically by adding static and dynamic types of loads to the system. It is known that a major portion of load is induction motors. In this paper, microgrid test system will be expended to a point that various combinations of static and dynamic loads can be considered as loads. After modeling part, effectiveness of the microgrid voltage stabilizer (MGVS) developed for microgrids that have only constant power type of loads will be studied under various combinations of static and dynamic loads.*

Keywords: *Load modeling, Power grids, Voltage control, Voltage stability.*

I. NOMENCLATURE

Subscript m – imaginary axis;
Subscript r − real axis;
V_0, P_0, Q_0 − initial conditions of the system, (Voltage, active power, reactive power respectively);
a_1 to a_6 − Parameters of ZIP load model;
K_{pf}, K_{qf} − Frequency sensitivity parameters;
e' −First cage voltage;
Ω_b − Base radian electrical frequency;
σ – Slip;
x_R − Cage rotor reactance;
r_R − Cage rotor resistance;
T_M − Mechanical torque applied at the shaft;
T_e − Electrical torque;
x_m − Magnetization reactance;
x_s − Stator reactance;
r_s − Stator resistance;
H − Shaft inertia constant;
$V_{i\,des}$ − Desired voltage
$V_{i\,dyn}$ − Dynamic voltage
$\Delta V_{i\,err}$ − Per unit (pu) difference between the desired voltage and the dynamic voltage
ΔV_{err} − Total voltage deficiency
K − Gain constant
T_1, T_2 − Time constants
V_{MGVS} − Output of the controller
$\propto_1, \propto_2, \ldots . \propto_l$ −The weighting factors for load buses

II. INTRODUCTION

Load representation is a critical issue on approaching power system modeling realistically. Loads are still considered as one of the most uncertain components of a power system to model because of their randomness, different timescale properties and their statistical nature. The results of the stability studies of power systems depend on how the load models represent the real load types. Several studies have shown the crucial effect of load representation in voltage stability studies [1] - [2]. Induction motors (IM) are used for representing the dynamic part of the load models. Depending on the type of the user profile, between 50% and 70% of the entire load consists of three phase IMs [3]. Static Polynomial (ZIP) load types are also commonly used and can be classified into constant impedance (Z), constant current (I) and constant power (P) load. The power has a quadratic dependence on voltage for Z load. For an I load, this dependency is linear, and power is independent of voltage changes for P type of load.

In addition to load representation and modeling, increasing power demand is another leading issue exists for utility companies. More demand on power is stressing the generation system capabilities and transmission lines. Low efficiency of central plants and transmission and generation losses plus frequent power outages cost the United States hundreds of billion dollars per year [4]. Researchers are looking for alternatives that can fix those pricey problems without adding new

transmission lines. Integration of the distributed energy sources to main grid can be a possible answer for these questions but this concept has its own shortcomings. Therefore, researchers and scientists proposed a network called "Microgrid".
Several blackouts have been associated with voltage stability problems in a power system [5]-[6]. A fast voltage collapse can be avoided by using available dynamic reactive power capabilities sufficiently. Transferring the reactive power within long distances causes massive voltage drop for typical power systems. But this is not the case for microgrid systems. Sustaining the dynamic voltage stability for microgrids can be possible with coordinated compensation of reactive power sources because electrical distance between the loads and the sources of the reactive power are relatively short. This concept has been used for designing Microgrid Voltage Stabilizer (MGVS) [7].

In this study, a 21- bus microgrid system, as shown in Fig. 1, run by diesel engine generators (DEG) will be used and load types will be considered as IM and ZIP loads to make the microgrid environment as realistic as possible to investigate voltage stability issues. After adding the IM and ZIP loads to microgrid model, effectiveness of the MGVS will be investigated for all load types.

III. MICROGRID

A microgrid is a distributed energy system which is a part of a large power system and it is supported by one or more distributed generation (DG) units. Microgrids are almost 85% efficient and have combine heat and energy applications and lesser transmission losses [8]. Its capability of operating in parallel with the grid or being able to operate in islanding mode during power outages and disturbances provides higher flexibility and reliability of operation. In islanding mode, microgrids retain power availability, avoid lost productivity and blackouts.

The aim of a microgrid is to provide a value to both customer and utility by supplying to local loads [9]. Higher power quality, reduction in environmental pollutants, higher reliability of power distribution, and decreasing power line congestion can be listed as some of the benefits of the integration of microgrids into utility grid.

IV. MODELING OF LOADS

Previous studies on modeling of the microgrid itself [10] is extended to a point that all of its loads at the microgrid are converted to static and dynamic type of loads from constant power loads. In this section, modeling of dynamic and static loads will be presented.

1. STATIC POLYNOMIAL (ZIP) LOAD

ZIP Load Model is one of the oldest load representations. It is called ZIP because it is a combination of Z, I and P type of loads. Following equations represent the static polynomial load model [11]

$$P = P_0 \left[a_1 \left[\frac{V}{V_0}\right]^2 + a_2 \left[\frac{V}{V_0}\right] + a_3 \right] (1 + K_{pf} \Delta f) \qquad (1)$$

$$Q = Q_0 \left[a_4 \left[\frac{V}{V_0}\right]^2 + a_5 \left[\frac{V}{V_0}\right] + a_6 \right] (1 + K_{qf} \Delta f) \qquad (2)$$

2. INDUCTION MOTOR

In this study, third order single cage induction motor has been used [12]. The single-cage induction motor's simplified electrical circuit can be seen in Fig. 2. The equations are formulated in terms of real and imaginary axes, with respect to the network reference angle.
The network and stator machine voltage is:

$$v_r = -V \sin \theta \qquad (3)$$

$$v_m = V \cos \theta \qquad (4)$$

The power absorptions are:

$$P = v_r i_r + v_m i_m \qquad (5)$$

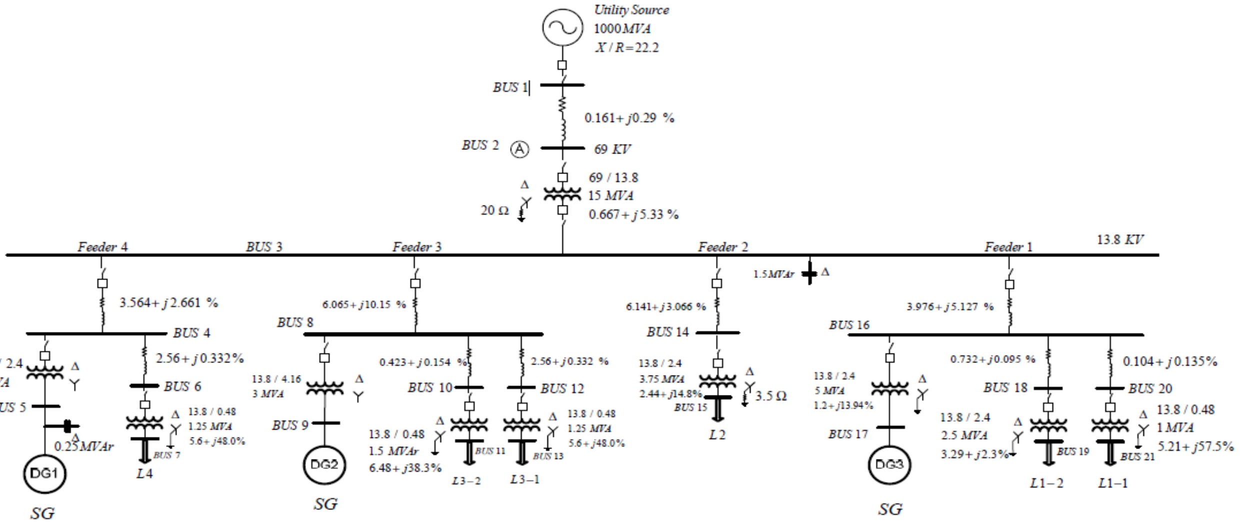

Figure 1. 21- Bus Microgrid System.

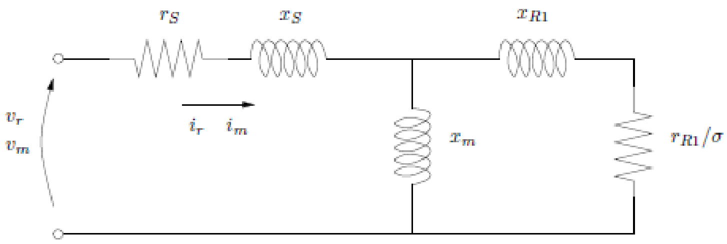

Figure 2. Simplified electrical circuit for single cage IM.

$Q = v_m i_r + v_r i_m$ (6)

In terms of the voltage behind the stator resistance r_s, the differential equations are [12]:

$\frac{d}{dt} e_r^{'} = \Omega_b \sigma e_m^{'} - \frac{e_r^{'} + (x_0 - x^{'}) i_m}{T_0^{'}}$ (7)

$\frac{d}{dt} e_m^{'} = -\Omega_b \sigma e_r^{'} - \frac{e_m^{'} + (x_0 - x^{'}) i_r}{T_0^{'}}$ (8)

The link between state variables, currents and voltages is:

$v_r - \frac{d}{dt} e_r^{'} = r_s i_r + x^{'} i_m$ (9)

$v_m - \frac{d}{dt} e_m^{'} = r_s i_m + x^{'} i_r$ (10)

where $x_0, x^{'}$ and T_0 can be obtain from the motor parameters.

$x_0 = x_s + x_m$ (11)

$x^{'} = x_s + \frac{x_{R1} x_m}{x_{R1} + x_m}$ (12)

$T_0^{'} = \frac{x_{R1} + x_m}{\Omega_b r_{R1}}$ (13)

At last, the mechanical equation is:

$\frac{d}{dt} \sigma = \frac{T_m(\sigma) - T_e}{2H_m}$ (14)

where the electrical torque is:

$T_e = e_r^{'} i_r + e_m^{'} i_m$ (15)

V. MICROGRID VOLTAGE STABILIZER

The MGVS has a similar functionality compared to a power system stabilizer (PSS) in terms of approaching voltage stability problem of a power system. The PSS gives an input to the excitation system of a generator to bring voltage stability to a power system. In order to prevent any voltage collapse, The MGVS gives an input to reactive power loops of DGs or the excitation systems, which lets DGs to kick in more reactive power into the microgrid. By implementing this method, using of costly dynamic reactive sources like capacitor banks, SVC or STATCOM can be avoided. The MGVS model and its simplified version can be seen in Fig. 3 and Fig. 4 respectively.

The MGVS input is a measurement of the per unit (pu) difference ($\Delta V_{i\ err}$) between the desired voltage ($V_{i\ des}$) and the dynamic voltage ($V_{i\ dyn}$). This voltage deficiency is calculated for all the load buses [7].

$\Delta V_{i\ err} = \frac{V_{i\ des} - V_{i\ dyn}}{V_{i\ des}} \qquad i = 1,2,..l$ (16)

Based on the importance of the bus, weighting factors for all buses are defined. In order to get a total voltage deficiency (ΔV_{err}) of the system, a weighted average of $\Delta V_{i\ err}$ is taken. A lead/lag block consisting of gain constant (K) and time constant T_1 and T_2 takes the ΔV_{err} as an input. As shown in Fig. 3, V_{MGVS} is the output of this MGVS controller [7].

$\Delta V_{err} = \frac{\propto_1 \Delta V_{1\ err} + \propto_2 \Delta V_{2\ err} + \ldots \propto_l \Delta V_{l\ err}}{\propto_1 + \propto_2 + \cdots + \propto_l}$ (17)

The weighting factors for load buses are $\propto_1, \propto_2, \ldots . \propto_l$. For this study, all $\propto$ values are equal to each other because loads at all buses are considered equally important.

The block diagram in Fig. 4 can be implemented in MATLAB. The corresponding differential equations representing the MGVS are given below.

$\dot{x}(t) = -\frac{1}{T_1} x(t) + \frac{K(T_1 - T_2)}{{T_1}^2} \Delta V_{err}$ (18)

$V_{MGVS}(t) = x(t) + K \frac{T_2}{T_1} \Delta V_{err}$ (19)

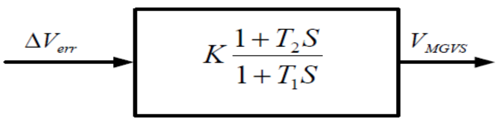

Figure 3. Microgrid Voltage Stabilizer

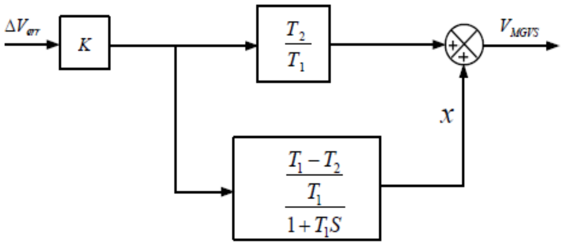

Figure 4. Simplified Microgrid Voltage Stabilizer Model

VI. SIMULATION AND RESULTS

After modeling of the microgrid system and its components, voltage stability of the system will be studied by implementing a three phase short circuit fault to a selected bus. In this paper, MATLAB programming environment is used to model the 21-bus microgrid system that has three diesel engine generators and 6 loads and to implement the fault conditions [13]. Fig. 1 shows the details of the microgrid system used for this study. There will be two case studies. In first case study, load types will be considered as either 100% ZIP or 100% IM type and response of the system after disturbances will be evaluated. For the second case study, load types will be considered as 50% ZIP and 50% IM type. The results will be used to compare the cases of with and without presence of the MGVS. This will help us to understand the behavior of MGVS with ZIP and IM type of loads and its effectiveness.

Case study 1: Three phase short circuit fault at Bus 7 with 100% ZIP and 100% IM Loads

In this case study, a three phase short circuit fault is applied to Bus 7 for 1.5 sec. The disturbance starts at 0.5 sec. and overall simulation time is 7 sec. Bus Voltages, Active Power and Reactive Power for Bus 15 have been plotted separately for various load types with and without presence of MGVS as listed below.

1) 100% I M
2) 100% I M with MGVS control
3) 100% P
4) 100% P with MGVS control
5) 100% Z
6) 100% Z with MGVS control

In each case, only one type of load is considered and all results are shown in one plot for comparison. Aim for having only one type of load is for observing the system behavior for those loads individually. Depending on load types, the voltage at Bus 15 drops at the time of fault to a point that is all different for each case. As it can be seen from the Fig. 5, the biggest drop took place with 100% P load and least drop was observed with 100% Z load. Without presence of MGVS voltage drops around 0.92 pu and stay around that point. The MGVS works effectively for all load types to compensate the voltage drop. Voltage turns back to nominal point in 1.5 s. The results show that when the MGVS is active, the response of system after the fault for covering the voltage is alike for all load types. But when we look at Fig. 6 for active power and Fig. 7 for reactive power response of the system, they are all different for each case.

Z and P loads are the upper and lower limit for voltage dependency of active and reactive power of ZIP load respectively. Any other percentage of these Z-I-P load types will be in that range. Active and reactive power at all load buses for 100% P load is constant because they are independent from voltage changes. Largest decrease on producing active and reactive power happened for 100% Z load because its dependence of voltage is quadratic. At the times of fault and the fault clearing, 100% IM load has instant pick values for reactive power as in Fig 7. With presence of the MGVS, there is a significant increase for reactive power and active power for all load types. It is normal to observe this behavior because MGVS is improving the voltage profile of the system by using the reactive power compensation.

Case study 2: Three phase short circuit fault at Bus 7 with 50% ZIP and 50% IM Loads

Depending on the type of the user profile, between 50% and 70% of the entire load consists of three phase IMs. For this case study, 50% ZIP and 50% IM Loads is considered in order to make the load profile more realistic and suitable for real life applications. A Three phase short circuit fault is applied to Bus 7 for 1.5 s. Total simulation time is 7 s. Bus Voltages, Active Power and Reactive Power for Bus 15 have been plotted for various load types for the case of with and without presence of MGVS as listed below. Results are shown in one plot for comparison for each case.

1) 50% P + 50% IM with MGVS control
2) 50% P + 50% IM
3) 50% Z + 50% IM with MGVS control
4) 50% Z + 50% IM

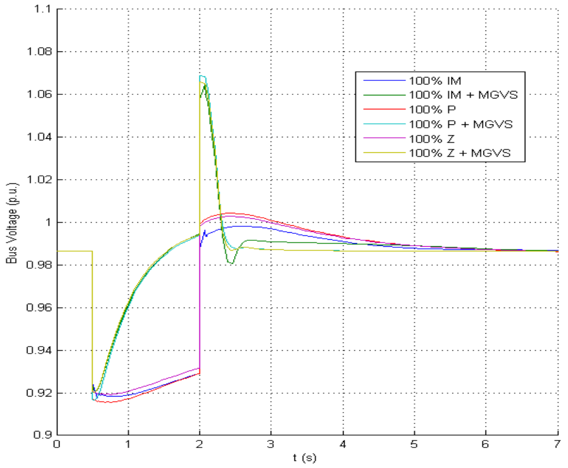

Figure 5. Comparison of Bus Voltage at Bus 15 for Case Study 1.

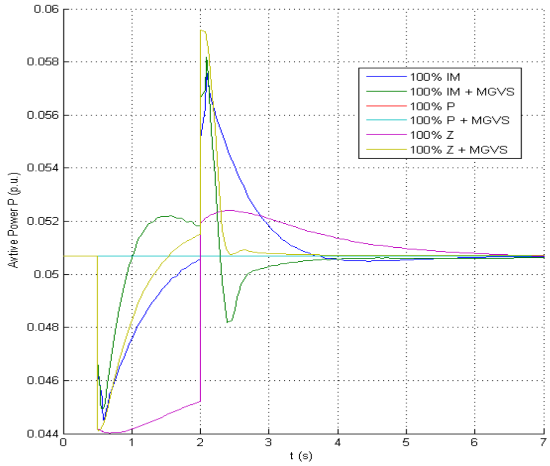

Figure 6. Comparison of Active Power at Bus 15 for Case Study 1.

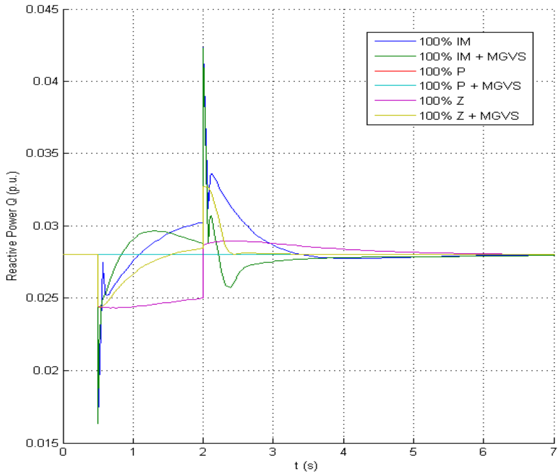

Figure 7. Comparison of Reactive Power at Bus 15 for Case Study 1.

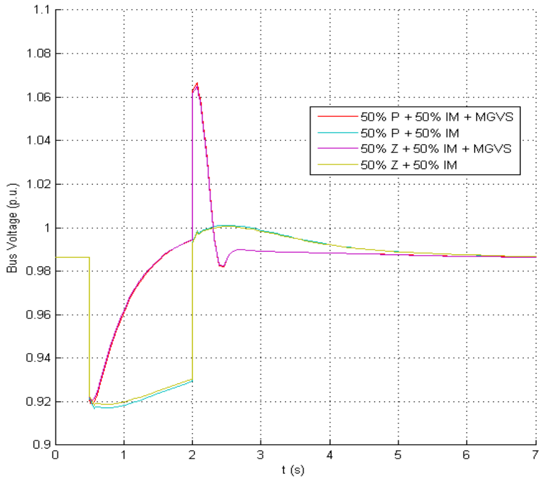

Figure 8. Comparison of Bus Voltage at Bus 15 for Case Study 2.

In this case study, we have 50% fixed IM load. 50% ZIP load considered as 50% Z and 50% P type of load in order to see the range of possible variations. Depending on Z and P loads, the voltage at Bus 15 drops to a point that is slightly different for each case. As it can be seen from Fig. 8, voltage drop is more for the case having P load compared to the case having Z load. Without presence of MGVS voltage drops around 0.92 pu and stay around that point. When the MGVS is active, voltage turns back to nominal point in 1.5 s. and there is an 8% improvement in bus voltages. But when we look at Fig. 9 for active power and Fig. 10 for reactive power response of the system, they are all different. As it was observed at the case study 1, largest drop for active and reactive power occurred at the case having Z load because its dependence to voltage is quadratic. At the times of fault and fault clearing, instant pick values for reactive power can be seen because of IM load for all cases. With presence of the MGVS, there is a significant increase for reactive power and active power for all load types. MGVS is using the available reactive power capabilities to improve the voltage profile of the system.

VII. CONCLUSION

Modeling of static and dynamic loads of a 21-bus microgrid test system and successful implementation of three phase short circuit fault with variable ZIP load and dynamic IM load has been presented using MATLAB. By using this simulation study, it was observed that the static ZIP and IM load models can have different load power characteristics depending on the relation with the voltage. Most of the real load types that are being tried to model have all variety of load types like industrial, residential and agricultural. Combining ZIP and IM loads made microgrid system more realistic because this is the common practice in real life. By changing the percentage of the ZIP load parameters and overall percentage of IM load, desired load characteristics can be accomplished. By using this test system, effectiveness of MGVS on voltage stability enhancement has been investigated. After testing MGVS with pure ZIP, pure IM and combination of ZIP+IM loads, results showed that MGVS is kicking enough reactive power to the system to prevent voltage collapse and it is enhancing the voltage profile of load buses for each type of loads successfully.

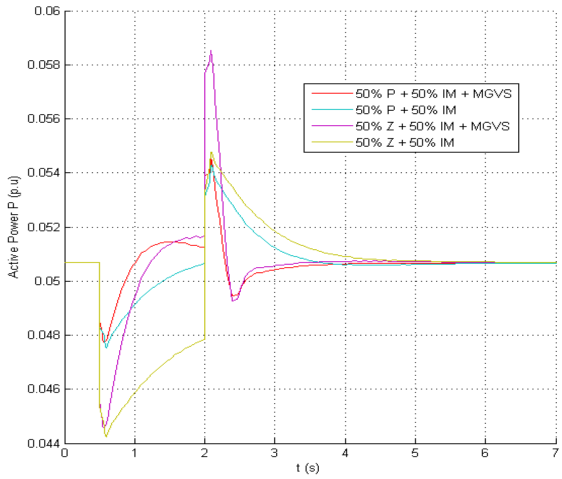

Figure 9. Comparison of Active Power at Bus 15 for Case Study 2.

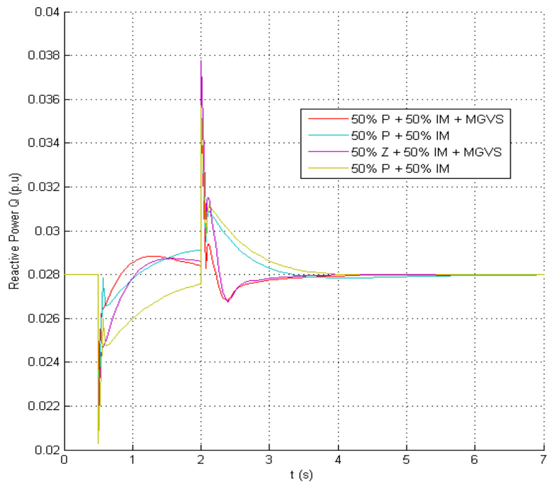

Figure 10. Comparison of Reactive Power at Bus 15 for Case Study 2.

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