

Modal Analysis of Power System with a Microgrid

Burak Yildirim, Muhsin Tunay Gençoğlu

Abstract—A microgrid (MG) is a small power grid composed of localized medium or low level power generation, storage systems, and loads. In this paper, the effects of a MG on power systems voltage stability are shown. The MG model, designed to demonstrate the effects of the MG, was applied to the IEEE 14 bus power system which is widely used in power system stability studies. Eigenvalue and modal analysis methods were used in simulation studies. In the study results, it is seen that MGs affect system voltage stability positively by increasing system voltage instability limit value for buses of a power system in which MG are placed.

Keywords—Eigenvalue analysis, microgrid, modal analysis, voltage stability.

I. INTRODUCTION

ENERGY is at the center of the developments that we have realized both economically and socially in our time. Today, the need for electricity is increasing rapidly due to increasing population and industrialization, and as a result, the demand for electricity is increasing equally. In addition, the use of high voltage transmission lines due to the fact that the power generation centers are remote from living centers and the expansion of the distribution systems has complicated operating conditions and control procedures. Due to the reasons mentioned above, the supply of electricity over large power plants is no longer preferred due to geographical and environmental limitations, as well as political and technical reasons. Instead, the local use of small power and distinctive energy sources has become widespread worldwide [1], [2].

Evolutionary changes in the regulatory and operational climate of traditional electrical services and the emergence of smaller production systems such as micro-turbines have created new opportunities for electricity generation by electric users. In this context, distributed energy sources “The small generators in the user’s sites in the places where the generated energy (both electric and thermal) are produced” have emerged as a promising option to meet the increasing needs of the customer for electrical energy, focusing on reliability and power quality. CERTS (Consortium for Electric Reliability Technology Solutions) refer to the MG concept as a collection of loads and micro resources that operate as a single system that provides both power and heat.

Most of the micro resources must be based on power electronics in order to provide the necessary flexibility to guarantee working as a single unified system. This control flexibility must present itself to the bulk power system as a

single controllable unit that meets local needs for reliability and security [3]. Understanding the process behind the design of a MG requires defining what a MG is. The most commonly accepted definition of the MG concept is a collection of small resources, storage systems, and loads that present itself as a single, flexible and controllable entity in the main network [4].

Voltage stability is defined as the protection of the steady voltage value of all buses after a power system has encountered any disturbing effect while in a given initial condition. Voltage instability can lead to the consequences of a progressive decrease or increase in the voltage of some buses [5]. Power system voltage stability is a mandatory issue for operating and planning the safety, reliability, efficiency and economics of power systems.

The connections of the MGs to the power systems at various levels affect the stability of the power system. In recent years, the effects of MG and MG-related systems on operation and protection are being investigated. However, studies on the stability of the MG-related power systems are limited. There are commonly publications in the literature that examine the effects of renewable energy sources on power system stability and control and stability of single, often islanded, MGs [6], [7]. We can list some of them as following; the effect of wind penetration on power system stability was investigated in [8], while in [9], the effect of solar penetration on stability of power systems, and in [10]–[13] control and stability of MG are investigated [8]–[13].

The remainder of this study was organized as follows. Section II provides information on the methodology used in the study, and in this chapter, It is described the first concept of voltage stability and the methods of analysis in which the stability studies were carried out. In Section III, units, composing of MG are shown. The results of the numerical analysis obtained in the study are given in Section IV. The last part of the study is devoted to the main conclusions and contributions of this work.

II. METHODOLOGY

The main purpose of this publication is to show the changes that will occur in instability limit of buses voltage in the power system voltage stability in the case MG is added to the power system. For this purpose, voltage stability was explained and a modal analysis method was expressed in order to examine its effects.

A. Voltage Stability

Voltage stability is the ability of a power system to keep the voltage values in all buses within the given limits in normal operating times and after encountering a disturbance. This sustainability can be assessed against a small or large disturbance, and at the same time it can be examined short or

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long time after the disturbance has occurred [5], [14].

Power system voltage stability studies are usually done in static and dynamic forms in the literature. The dynamic voltage stability of the power system is not possible to evaluate with the static form corresponding to long-term stability evaluations involving power flow studies. In dynamic form, time domain simulation is used with dynamic models of generators, loads, automatic voltage regulators, and other components of the power system. Both short-term and long-term voltage stability evaluations are performed with dynamic form [5].

B. Modal Analysis

In addition to small signal stability analysis, eigenvalues and eigenvectors can also be used to evaluate sensitivities at the same time. Modal analysis is a very suitable tool to characterize the dynamic presence of a power system around its working point [15]. In particular, an interesting approach is the modal analysis evaluation of power flow Jacobian matrix [16]–[18], [19].

The voltage characteristics of a power system can be analyzed by linearizing the power flow equations and analyzing the resulting sensitivity matrices around a working point. The developments in computational algorithms have made these techniques efficient for analyzing large-scale systems and taking into account almost all the important factors that affect the phenomenon [20]. Using the continuous state system model, the method calculates a certain number of eigenvalues and associated eigenvectors of a decreasing Jacobian matrix. Each of the eigenvalues associated with a mode of a voltage/reactive power change provides a relative measure of the closeness to voltage instability. Eigenvectors are used to provide information about the power grid elements and generators involved in each mode and to define the mode format. The simultaneous iteration method, which is very suitable for applications involving large power systems, is used for the selective computation of appropriate eigenvalues [18].

The modal analysis involves calculating a small number of eigenvalues that contain the appropriate characters of the generators, loads, reactive power balancing devices, and HVDC converters that maintain QV relationships in the power grid and associated eigenvectors of the reduced Jacobian matrix. However, using the reduced Jacobian instead of the system state matrix, the voltage and reactive power characteristics are concentrated. The Jacobian eigenvalues define the different modes in which the system can become unstable. The magnitude of the eigenvalues is a relative measure of closeness to instability. On the other hand, the eigenvectors provide information on the mechanism of loss of voltage stability. Fast analytical algorithms for the selective calculation of a small number of small eigenvalues make suitable the approach for the analysis of large complex power systems. In addition, with the appropriate choice of system models, the method can be used to analyze instantaneous power flows that represent different time periods following major system failures [16]. Modal analysis is used to evaluate

voltage stability as follows.

The decreasing Jacobian matrix of the system is obtained as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \quad (1)$$

The linearized steady state system power voltage equations are given as: Here; ΔP : The increase in the real power of the bus, ΔQ : The increase in the reactive power injection of bus, $\Delta\theta$: The increase in voltage angle of the bus, ΔV : The increase in voltage magnitude of the bus shows.

If the conventional power flow model is used for voltage stability analysis, the Jacobi matrix in Equation (1) is the same as the Jacobian matrix used when the power flow equations are solved using the Newton-Raphson technique. System voltage stability is affected by both P and Q . However, we evaluate the stability of the voltage at each operating point, taking into account the increasing relationship between P and Q and V . Although the incremental changes in P are neglected in the formula, the effects of power transfer levels or load changes in the system are accounted for in the increased correlation between Q and V at different operating points. To reduce (1), $\Delta P \approx 0$ is taken and then:

$$\Delta Q = [J_{QV} - J_{Q\theta}J_{P\theta}^{-1}J_{PV}]\Delta V = J_R\Delta V \quad (2)$$

and

$$\Delta V = J_R^{-1}\Delta Q \quad (3)$$

where

$$J_R = [J_{QV} - J_{Q\theta}J_{P\theta}^{-1}J_{PV}] \quad (4)$$

is written. Here, J_R is termed as decreasing Jacobian matrix of system. J_R is the matrix that directly correlates the reactive power injection and bus voltage magnitude. Eliminating real power and angles from the system's steady state equations allows us to focus on minimizing the computation as well as working on the system's reactive demand and resource problems.

$$J_R = \xi \Lambda \eta \quad (5)$$

ξ : The right eigenvector matrix of J_R , η : The left eigenvector matrix of J_R , Λ : The diagonal eigenvalues of J_R and,

$$J_R^{-1} = \xi \Lambda^{-1} \eta \quad (6)$$

from (3) and (6)

$$\Delta V = \xi \Lambda^{-1} \eta \Delta Q \quad (7)$$

Or,

$$\Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q \quad (8)$$

where ξ_i is i. column right eigenvector of J_R and η_i is i. row left eigenvector of J_R . Similar to the concept of linear dynamic system analysis, each λ_i eigenvalue and the associated ξ_i and

η_i right and left eigenvectors of the system define i. the mode.
i. modal reactive power change is below.

$$\Delta Q_{mi} = K_i \xi_i \tag{9}$$

where;

$$K_i^2 \sum_j \xi_{ij}^2 = 1 \tag{10}$$

with ξ_{ij} the j . element of ξ_i , i . modal-related voltage change is as:

$$\Delta V_{mi} = \frac{1}{\lambda_i} \Delta Q_{mi} \tag{11}$$

When the reactive power change is along the direction of ξ_i , the associated change in voltage is also at the same direction. Further, its size is strengthened with a factor equal to the magnitude of the i . eigenvalue. In this sense, the magnitude of each λ_i eigenvalue determines the weakness of the associated modal voltage. If $\lambda_i = 0$, Because any change in modal reactive power will cause infinite modal voltage change, i . modal voltage will collapse. In (8), let $\Delta Q = e_k$, where e_k , has all its elements zero except the k . one being 1. Then,

$$\Delta V = \sum_i \frac{\eta_{ik} \xi_i}{\lambda_i} \tag{12}$$

with η_{ik} the k . element of η_i , V-Q sensitivity at bus k ,

$$\frac{\partial V_k}{\partial Q_k} = \sum_i \frac{\eta_{ik} \xi_i}{\lambda_i} = \sum_i \frac{P_{ki}}{\lambda_i} \tag{13}$$

If the Jacobian eigenvalues are all positive, the system is voltage stable. For small system stability studies, all eigenvalues must be negative in order for the system to be voltage stable. Positive eigenvalue condition for voltage stability in modal analysis can lead to a little head confusion. When the system is stressed, the eigenvalues of J_R decrease to the system voltage stability critical point; at least one of the eigenvalues of J_R is zero.

If some of the eigenvalues of J_R are negative, the system voltage stability exceeds the critical point, because when the system is stressed, the eigenvalues of J_R go from positive to zero to negative. While the magnitudes of the eigenvalues provide a relative relation of proximity to instability, they do not provide a complete measurement because the problem is not linear. This is parallel to the damping factor in the small signal stability analysis showing the degree of damping, but is not an exact measure of stability margin. The application of modal analysis is to help in determining how stable the system is how much extra load or power transfer level should be added and, when the system reaches voltage stability critical point, to determine the voltage stability critical areas and to describe the mechanism of instability by identifying elements which participate in each mode [21].

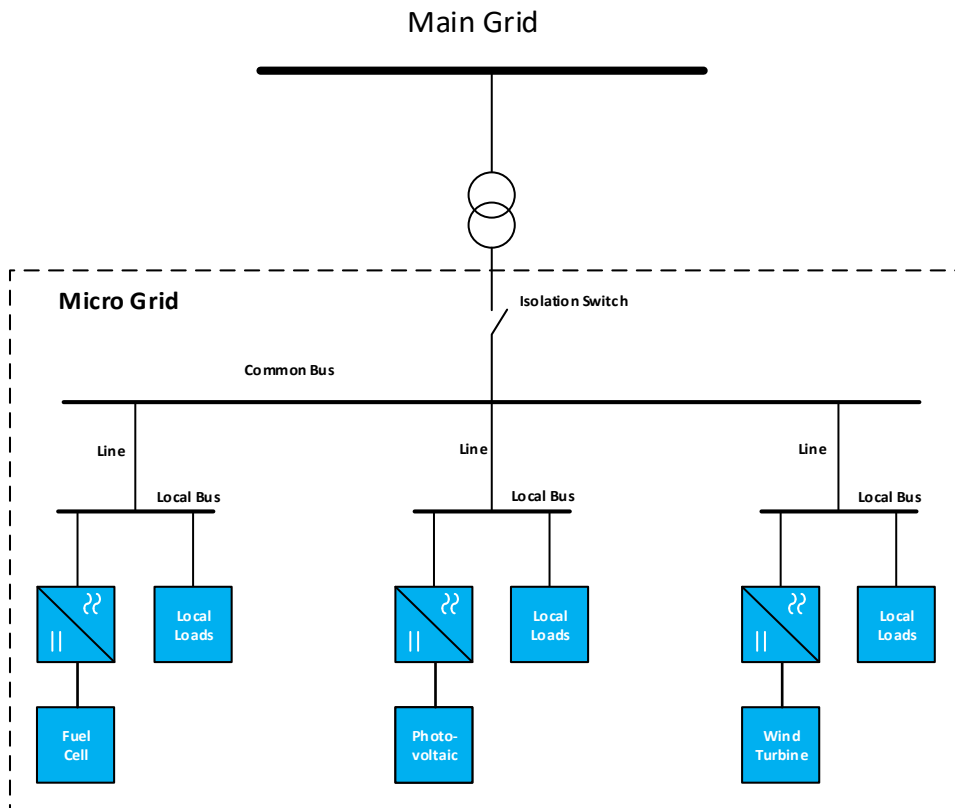


Fig. 1 Model block diagram of Inverter-based MG

III. MICROGRID MODEL

The concept of smart grids refers to the development of electricity networks. Smart grid is an electrical network that intelligently integrates all user actions connected to the network for continuous, economical and secure electricity distribution. The realization of active distribution networks requires the application of new system concepts. In addition, MGs, which are described as "building blocks of intelligent networks", are perhaps the most promising new network structure. The MG organization includes DGs containing micro-generations with distribution-level storage devices and controllable loads [22].

The usage rates of MG and DG units in electric power systems are increasing day by day; the main reasons for this are the short construction time of the plant, different source options, improved power quality, and reduced transmission losses and increased system reliability. In addition, the use of renewable energy sources as DG sources has also given a great impetus to this increase [23].

MG added to the test system was created in accordance with this model to demonstrate the effect of MG on Power System Oscillatory Stability. Details of the models of the renewable energy sources forming the MG can be found in [9], [20], [24]-[27].

IV. NUMERIC RESULTS

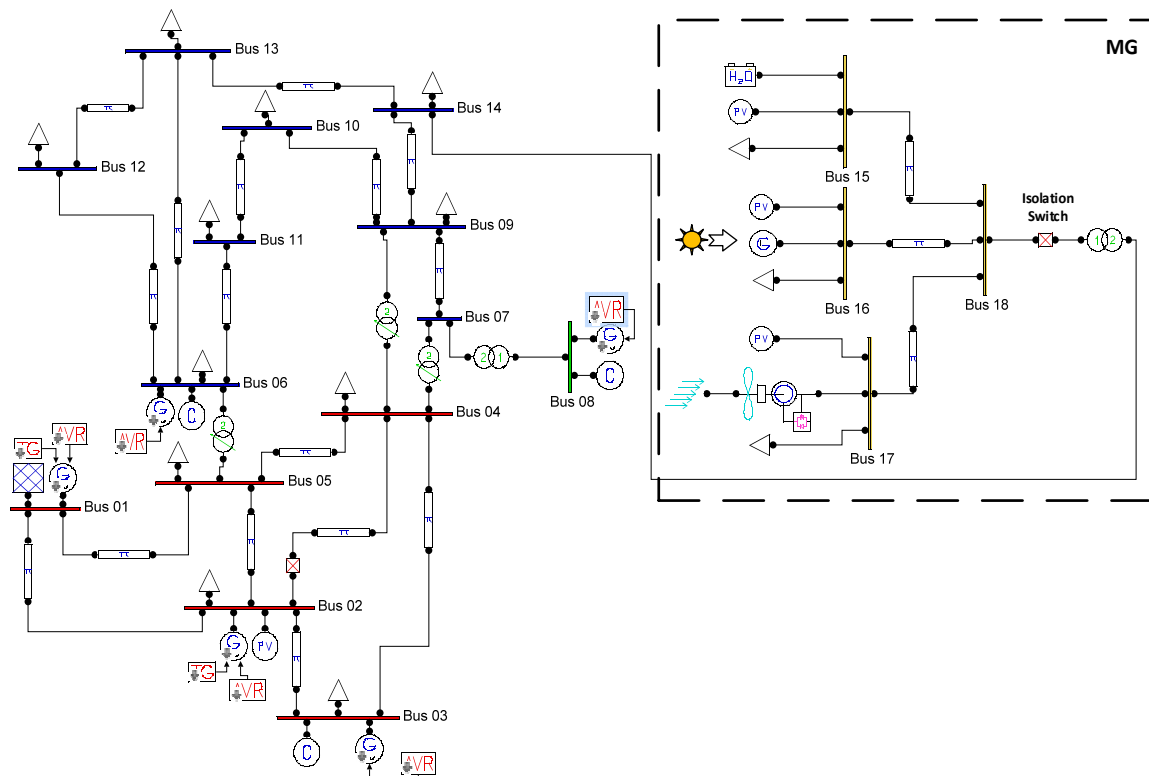


Fig. 2 IEEE 14 bus system

A. System Description

All numerical studies were performed using PSAT [28], an open source toolbox with MATLAB base. The IEEE 14 bus power system used in simulation studies is shown in Fig. 2. MG system installed in the study is connected to bus 14 in the IEEE 14 bus system. The reason of having been selected of bus 14 is that power loss rate is the lowest when the bus 14 has MG in the system, and the bus 14 is the weakest bus in the system. The power ratios of the units forming the MG system are selected as follows; FC 2 MW, PV 5 MW and WTG 10 MW. As stated in [29], PV, WTG and FC, which have converter and inverter interfaces, have the ability to absorb and inject reactive power to power system.

B. Modal Analysis

Modal analysis studies have been carried out in this section to demonstrate the effects of the MG on the power system. The results of the conducted analysis are shown in Tables I and II. Table I shows the results of modal analysis for the non-MG situation, while Table II shows the results of the modal analysis for the MG situation. In the IEEE 14 buses power system, there are generators (Bus 1, 2, 3, 6 and 8) in five buses and the eigenvalues of these buses are very high because the voltage is constant. The magnitude of the eigenvalues found here shows that is appropriate in terms of voltage stability. In the same way, since the power system with MG has generator unit for 8 bar, the eigenvalues belonging to this buses are also found to be quite high.

TABLE I
POWER FLOW SENSITIVITY ANALYSIS RESULTS OF 14 BUS BASIC POWER SYSTEM

Eigenvalues	Mostly associated bus	Real and Imaginary parts	Participation Factors									
			Bus 4	Bus 5	Bus 7	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14	
Eig Jlfr # 1	Bus 04	64.1837+0	0.54	0.45	0	0	0	0	0	0	0	0
Eig Jlfr # 2	Bus 09	38.5573+0	0	0	0.15	0.61	0.21	0	0	0	0	0
Eig Jlfr # 3	Bus 07	21.403+0	0.07	0.15	0.49	0	0.21	0.05	0	0	0	0
Eig Jlfr # 4	Bus 13	18.6371+0	0	0	0	0	0	0	0.18	0.76	0.04	0
Eig Jlfr # 5	Bus 05	15.9795+0	0.28	0.31	0.02	0.04	0.16	0.15	0	0	0	0
Eig Jlfr # 6	Bus 14	2.6083 +0	0	0	0.06	0.19	0.23	0.1	0.01	0.03	0.32	0
Eig Jlfr # 7	Bus 12	5.4317 +0	0	0	0.01	0.03	0.12	0.13	0.3	0.15	0.22	0
Eig Jlfr # 8	Bus 12	7.4821 +0	0	0	0	0	0.03	0.1	0.47	0.03	0.34	0
Eig Jlfr # 9	Bus 11	11.0446 +0	0.08	0.06	0.23	0.1	0	0.43	0	0	0.05	0
Eig Jlfr # 10	Bus 01	999+0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 11	Bus 02	999+0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 12	Bus 03	999+0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 13	Bus 06	999+0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 14	Bus 08	999+0	0	0	0	0	0	0	0	0	0	0

TABLE II
POWER FLOW SENSITIVITY ANALYSIS RESULTS OF 14 BUS POWER SYSTEM WITH MG

Eigenvalues	Mostly associated bus	Real and Imaginary parts	Participation Factors										
			Bus 4	Bus 5	Bus 7	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14	Bus 18	
Eig Jlfr # 1	Bus 04	64.4236+0	0.54	0.45	0	0	0	0	0	0	0	0	0
Eig Jlfr # 2	Bus 09	38.7976+0	0	0	0.15	0.61	0.21	0	0	0	0.01	0	0
Eig Jlfr # 3	Bus 14	2.7308+0	0	0	0.05	0.16	0.20	0.09	0.01	0.02	0.22	0.2	0
Eig Jlfr # 4	Bus 18	4.8673+0	0	0	0.03	0.07	0.18	0.16	0.06	0.04	0.13	0.29	0
Eig Jlfr # 5	Bus 12	6.5756+0	0	0	0	0	0	0	0.69	0.15	0.01	0.11	0
Eig Jlfr # 6	Bus 11	10.688 +0	0.07	0.05	0.2	0.1	0	0.51	0	0	0	0.04	0
Eig Jlfr # 7	Bus 07	21.492 +0	0.07	0.15	0.49	0	0.21	0.05	0	0	0	0	0
Eig Jlfr # 8	Bus 13	19.79 +0	0	0	0	0	0.02	0	0.1	0.54	0.25	0.06	0
Eig Jlfr # 9	Bus 14	15.1079 +0	0.09	0.10	0.03	0	0	0.01	0.08	0.13	0.28	0.23	0
Eig Jlfr # 10	Bus 05	16.2368 +0	0.2	0.23	0	0.03	0.15	0.13	0.03	0.08	0.06	0.03	0
Eig Jlfr # 11	Bus 01	999+0	0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 12	Bus 02	999+0	0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 13	Bus 03	999+0	0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 14	Bus 06	999+0	0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 15	Bus 06	999+0	0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 16	Bus 15	999+0	0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 17	Bus 16	999+0	0	0	0	0	0	0	0	0	0	0	0
Eig Jlfr # 18	Bus 17	999+0	0	0	0	0	0	0	0	0	0	0	0

When the results of Tables I and II are examined, the most critical buses in terms of stability is the bus 14 which has the smallest eigenvalue. Eigenvalues of all buses were found to be greater than zero both in power system with MG and in base power system. This means that all the buses have $\partial v / \partial q > 0$ and as a result they are stable systems in both systems. As Table I shows, the most critical bus with 2.6083 value is the bus 14. The eigenvalue of bus 14 was found to be 2.7308 by adding MG to the power system. As can be seen from this result, in terms of stability, MG addition has been positively influenced on the power system and provided the healing effects in the distance of the critical bus to the instability. As can be seen from Tables I and II, the addition of the MG has resulted in an increase in the eigenvalues of all the buses and the MG has generally contributed positively to the stability of the power system.

V. CONCLUSION

The MG effects on the power system voltage stability are examined and discussed in this article. The studies were made for the IEEE 14 bus benchmark system, and the integration of the MG into the grid was accomplished through this system. When looking at the results from the study, it was seen that MG integration has positively effects on system voltage stability by increasing system voltage instability limit value for buses of power system in which MG are placed. Modes of systems were obtained by modal analysis performed on the systems. As can be seen from this result, in terms of stability, MG addition has been positively influenced on the power system and provided the healing effects in the distance of the critical bus to the instability and MG has generally contributed positively to the stability of the power system.

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