Investigation the Impact of Length Increase of Lines on the Dynamic Performance of Microgrids

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Abstract: This paper presents a new method to evaluate the effect of line length on the dynamic performance of the inverter based micro-grids (MG) by using eigenvalue based sensitivity approach. Due to the location of partial loads and generators, the MGs can experience increased line length. Line length could increase when micro-sources (MS) and loads either geographically or electrically are located far from each other in a micro-grid. In this paper, first the effect of line length increase is investigated analytically and then a small-signal model of a prototype micro-grid is derived and the eigenvalue sensitivity of the system is considered for line length effect analysis. The analysis shows that the dynamic performance can be deteriorated which could eventually lead to instability when the line length line increases. The analytical results are verified using linearized small-signal model of a prototype micro-grid. Time domain simulations are also used for the validation of results. Moreover, a method is proposed to improve the dynamic performance of the system in presence of line length increment.

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1. Introduction

In general, a part of the power distribution network, with electrical and thermal loads and distributed energy resources that provides integrity, capability and control flexibility is called a micro-grid (MG) [1,2]. MG is connected to the power grid in normal conditions. But, the design, control and operation strategy of the MG is so that it can continue to work island and autonomously by providing its loads from power grid [3,4].

The resource controllers are a major part of the MGs structure. These controllers respond in a few milliseconds and use the local data of each source to control it [5,6]. Nowadays, more MGs are installed in the laboratory environments or in limited and small places which results in short length lines [7]. But in the real and modern distributed generation systems, especially in the urban and industrial areas, the producers and consumers are distributed in a vast area [8] which cause increase in the electrical length of the line and affect the MGs performance.

As mentioned before, one of the important aspects of a MG is its control strategy. Among different control strategies proposed for a MG [9], the decentralized and centralized control strategies can be identified as the major ones. The centralized control strategy uses high bandwidth communication links among micro-sources in order to transfer control signals among them and thus inherently would result in less reliability. The decentralized control strategy uses only local parameters and thus is considered to be more reliable [6,10]. This paper is focused on MGs with decentralized control strategy only.

This paper investigates the effect of line length on the dynamic behavior of MGs by using eigenvalue based sensitivity approach. Due to the location of partial loads and generators, the MGs can experience increased line length. Line length could increase when micro-sources (MS) and loads either geographically or electrically are located far from each other in a micro-grid. In this paper, first the effect of line length increase is investigated analytically and then a small-signal model of a prototype micro-grid is derived and the eigenvalue sensitivity of the system is considered for line length effect analysis. The analysis shows that the dynamic performance can be deteriorated which could eventually lead to instability when the line length line increases. The analytical results are verified using linearized small-signal model of a prototype micro-grid. Time domain simulations are also used for the validation of results. Moreover, a method is proposed to improve the dynamic performance of the system in presence of line length increment.

The reminder of the paper is organized as follows. The concepts of droop characteristics in Microgrids are briefly explained in Section 2. Section 3 discusses the small signal analysis of Microgrids. The proposed analyses for investigating the effects of line length increase on the dynamic of Microgrids are presented in Section 4. Section 5 gives some approaches for improving system performance over the long lines and finally, Section 6 presents some concluding remarks.

2. Droop Characteristics in Microgrids

In modern power systems, energy sources are typically large power plants which are connected to each other through the transmission lines with inductive characteristic. Using droop characteristics is a well-known technique in large power systems in order to properly share the demanded active and reactive power among generating stations. Such a technique has been also adopted in MGs with decentralized control strategy [11,12]. The expression for the droop characteristic between the active power and the frequency is given by the following equations:

$$f = f_0 - m_p \times P \qquad (1)$$

$$V = V_0 - n_p \times Q \qquad (2)$$

Where P and Q are the active and reactive power generation of the plant, respectively. Also, f and V are the frequency and voltage bus of power plant at operating point, respectively and f_0 , v_0, n_p and m_p are constants [11]. Eqn. (1) is sometimes called *Pf* or *Pω* characteristic. With an interpreting, the droop characteristics employ the frequency and voltage as a communication link to share the demanded active and reactive power among generating stations without any physical communication link.

In MGs and distributed generation systems, the resources are usually much smaller and are connected to each other through the distribution lines. Also, in the MGs which there is no central controller and each resource has an independent controller, usually the droop characteristics like large generators of power systems are suitable for sharing the active and reactive power between the sources[1].

Although the concepts of using droop characteristics in MGs and in large power systems are the same, the nature and size of components in MGs is such that it calls for special attention in applying this technique. In particular, despite droop characteristics of active and reactive power sharing among the sources used in the steady state, but these characteristics can also have influence on the system dynamics. Specifically, it will be shown that the droop characteristic given by (1) could result in instabilities with certain line lengths. This is explained in this paper, and will be elaborated in the main paper. In the following the dynamic relationship between a load and a source of power transmission and how it affects the droop characteristics are described.

Fig. 1 shows a typical distribution line model. The line parameters are shown in this Figure.

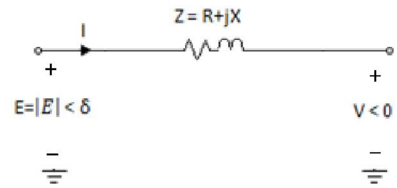

Fig. 1. Basic two-source system with a connecting line.

Given, $E\angle\delta$ as the supply voltage, $V\angle 0$ as the voltage at the end of the line and I as the current line of complex power. Based on Fig. 1, we can write

$$\bar{S} = P + jQ = \bar{E}.\bar{I}^* \qquad (3)$$

$$\bar{I} = \frac{E\angle\delta - V}{\bar{Z}} \qquad (4)$$

Based on Fig. 1, writing the expressions governing the power flow between two ac sources and by substituting (4) in (3) and simplifying the equations the following equations are obtained. Where θ is the impedance angle ($\bar{Z} = |Z|\angle\theta$).

$$P = \frac{|E|^2}{|Z|}.\cos\theta - \frac{V.|E|}{|Z|}.\cos(\theta+\delta) \qquad (5)$$

$$Q = \frac{|E|^2}{|Z|}.\sin\theta - \frac{V.|E|}{|Z|}.\sin(\theta+\delta) \qquad (6)$$

Where θ is the line impedance angle and other parameters are shown in the Fig. 1. Linearizing (2) around operating point and re-writing $\Delta\delta$ in terms of ΔP and ΔQ results in (7) and (8). the process of simplifying the mathematical details are avoided due to the limited size of the paper.

$$\Delta|E| = \left[\frac{|Z|.\cos(\theta+\delta_0)}{2|E_0.\cos\delta_0 - V|}\right] \times \Delta P + \left[\frac{|Z|.\sin(\theta+\delta_0)}{2|E_0.\cos\delta_0 - V|}\right] \times \Delta Q \qquad (7)$$

$$\Delta\delta = \frac{|Z|}{|E_0|.V.\sin(\theta+\delta_0)} \times \left(\left[\frac{2|E_0|.\cos\delta_0 - V - 2|E_0|.\cos\theta.\cos(\theta+\delta_0) + V.\cos^2(\theta+\delta_0)}{2|E_0|.\cos\delta_0 - V}\right] \times \Delta P + \left[\frac{-2|E_0|.\cos\theta.\sin(\theta+\delta_0) + V.\cos(\theta+\delta_0).\sin(\theta+\delta_0)}{2|E_0|.\cos\delta_0 - V}\right] \times \Delta Q \right) \qquad (8)$$

Where subscript *0* denotes operating point values. Assuming $|E_0| = V \approx 1$ *pu*. and substituting in (8) yields

$$\Delta\delta = \frac{|Z|}{\sin(\theta+\delta_0)} \times \left[\frac{2\cos\delta_0 - 1 - 2\cos\theta.\cos(\theta+\delta_0) + \cos(\theta+\delta_0)}{2\cos\delta_0 - 1}\right] \times \Delta P$$

$$= \frac{|Z|}{\sin(\theta+\delta_0)} \times f(\delta_0) \times \Delta P \quad (9)$$

Where

$$f(\delta_0,\theta) = \left[\frac{2\cos\delta_0 - 1 - 2\cos\theta.\cos(\theta+\delta_0) + \cos^2(\theta+\delta_0)}{2\cos\delta_0 - 1}\right] \quad (10)$$

Length increase results in the increase in the angle of the operating point (δ_0) which can result in changing the coupling between $\Delta\delta$ and ΔP. Fig. 2 shows the variation of $f(\delta_0)$ versus δ_0 for typical line parameters.

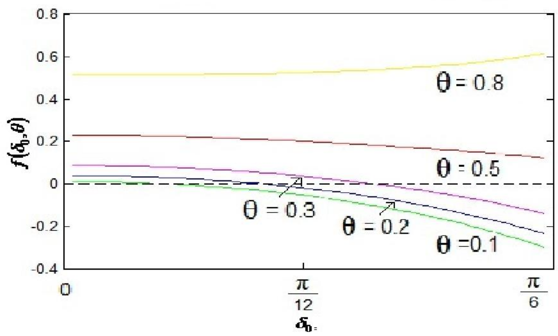

Fig. 2. Variation of $f(\delta_0)$ versus δ_0.

As can be seen from this figure, when the power angle increases in small θ which is corresponding to distribution systems, $f(\delta_0)$ initially decreases and then changes the sign .Moreover, close examination of (9) shows that the sign of $\Delta\delta / \Delta P$ and $f(\delta_0)$ is the same as the term $\frac{|Z|}{\sin(\theta+\delta_0)}$ is always positive with typical line parameters. As a result, $f(\delta_0)$ represents the dynamic relationship between active power and the power angle. now, with increasing the power angle (line length increase), the coupling between active power and power angle is first weakened and then its sign is changed. In other words, in line with low length, any dynamic increase in the power corresponds to increment in power angle. Versus in line with high length, any dynamic increase in the power does not correspond to increment in power angle.

If the coupling between active power and power angle is positive, which is the case in large power systems, the negative slop of *Pf* droop characteristic (i.e. (1)) will act as a negative feedback mechanism which eventually causes each source to pick up the appropriate share of power in an stable condition. However, if the inherent nature of system leads to negative coupling between active power and power angle, the conventional droop characteristics not only cannot provide any correction but also will lead to instability which is coused by a positive feedback mechanism. This is the basis of analytical studies presented in this paper and will be elaborated using real-world case studies and simulations.

3. Small Signal Analysis

To verify the analysis presented in previous section and investigate the small-signal stability of a MG in different conditions, a precise linearized model of the MG under study must be derived. Derivation of a reliable linearized model including all details of the main system and its controllers requires extensive work and is beyond the scope of this paper. Therefore, a verified detailed simulation platform which had been derived by the authors was modified and customized for these studies. For example, using a customized load flow program a new operating point is calculated after making even small changes in the system parameters in order to increase the accuracy of analysis. Fig. 3 shows the overall architecture of the simulation system.

All modeling and analysis are performed in the synchronous dq system. In order to extract the general model, the MG is divided into two parts: resources (including power electronic converters, passive filters and all controllers) and network (including communication lines and loads). According to existence several sources, each with its own coordinate system, one of these systems are intended as reference and equations of other inverters and network are transferred to the reference coordinate system. This issue is given schematically in Fig 3. In this figure, the first resource coordinate is considered as the reference coordinate system (dq). Further details of how to extract the small signal model is presented in [13].

Extraction of state space model is done by linearization around an operating point. However, in the nonlinear system, the operating point can have a major effect on the eigenvalues of the system . So the calculating of operating point in each case is necessary for the small signal model validation.

Operating point of the system is calculated in two parts. First, calculate the operating point with the outside perspective of DGs and second, calculate the operating point with the inside perspective of DGs. The first part consists of solving a power flow problem. Then in the second part, the operating point of DG is computed by using the obtained response of power flow problem and the steady state equations of resource [14].

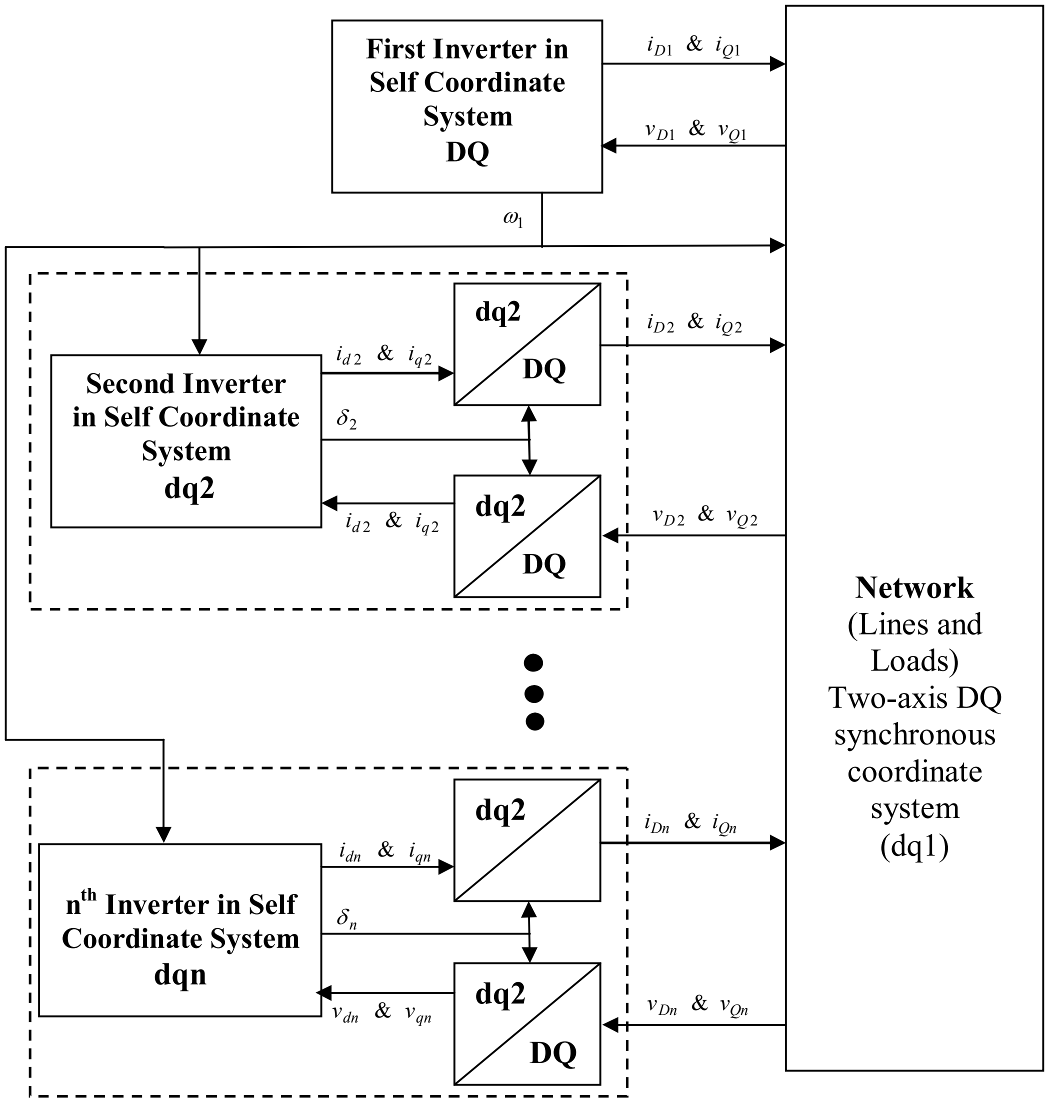

Fig. 3. The parts of Micro-grid and their relationship in view of modeling.

4. The Line Length Increase Effect on the Dynamic of Microgrids and Simulation Studies

In this section a prototype micro-grid is considered for the simulation studies to show how the line length increase leads to instability. The simulations are performed in the frequency domain using the small signal model system. Also, time domain simulations using PSIM software were used to validate the results obtained from small-signal linearized model in frequency domain.

Many simulations were carried out on real-world MGs (Wisconsin) to verify the analytical results. The single line diagram shown in Fig. 4 belongs to the MG described in [8] and considered as an example in this paper. This Microgrid includes two sources, five sets of three phase loads and a static switch to allow connection to the grid. The lines are the AWG 3 wire cable type with the length of 25 yd and 75 yd. The power of the system is provided by two AC-DC static converters. The system total load is 22.5 kw and 10.9 kVar which consists of three impedance loads with *PF*=0.9.

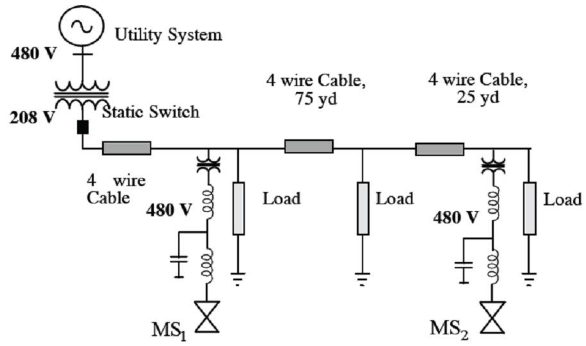

Fig. 4. The Micro-grid under study.

The droop characteristics, considered in this Microgrid, are the conventional type curves (active power-frequency and reactive power-voltage). The slopes of these curves are obtained based on the nominal active and reactive power of DG and allowable deviation values of frequency and voltage measurement. In this paper, the initial values of the interval changes are set to 0.2% and 0.02 pu for frequency and voltage, respectively. The details of this MG are presented in [8,9].

In order to study the dynamic performance of the system a disturbance is applied. This disturbance is considered as the increasing loads between the two lines with the value of 20% of total system load (4.5 Kw and 2.18 KVar). The small signal model with considering the equivalent current between two DGs as the input and the power generation of DGs, the voltages in different parts of the system and etc, as the output, models the behavior of the system. It is worth noting that, in order to increase the size of the system, the lengths of lines are increased simultaneously.

Fig. 5 shows the root locus plots when the line length increases. The parameter L shown in this plot is the ratio of new line length to the original line length used in actual setup. As mentioned in section III, for each change in the length of the line, the operating point is calculated and the linearization is performed around the new operating point.

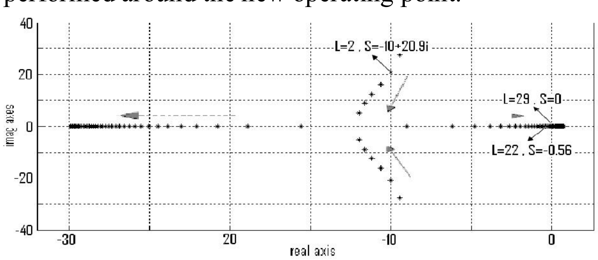

Fig. 5. Root locus of dominant poles for the line length increase from one to forty times .

As can be seen, instabilities began at L=29. This behavior is confirmed by running simulation in time domain. Fig. 6 show the time domain simulation results (obtained by PSIM software) for L=2 and L=22.

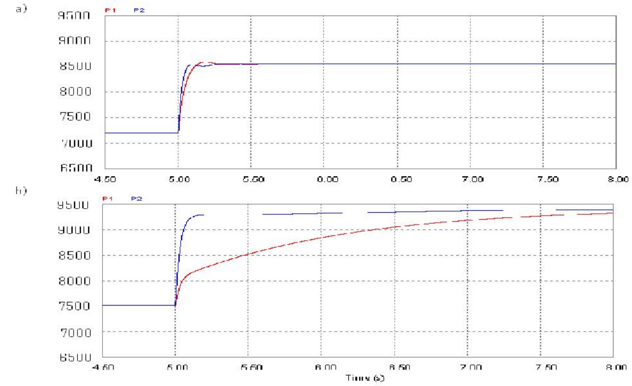

Fig. 6. Time domain simulation for a) L=2 and b) L=22.

The eigenvalues of the system corresponding to these lengths are shown in Fig. 5. As can be seen from Fig. 6, for L=2, system is stable and has a good dynamic response and for L=22, system is stable with slow response. Also, Fig. 7 shows the result of PSIM simulation with L=32 in which the instability at the output power of sources can be observed.

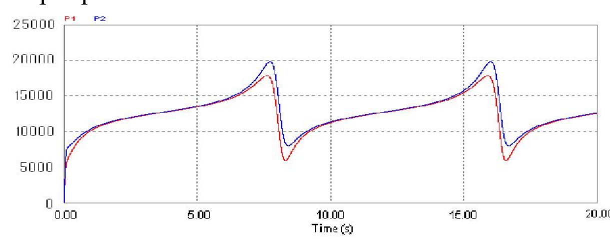

Fig. 7. Time domain simulation for L=32.

5. Techniques for Improving System Performance over the Long Lines

As was shown in Section IV, increasing the length of line can causes two types of problems for the system. The first problem is the slow dynamic of the system despite of preserved stability. Another problem is the loss of stability with longer lines. In this section, some of the ways to deal with these problems is discussed.

The locus of the effective eigenvalues, during the line length increase, for two different values of the slop of active power-frequency droop characteristic, is drawn in Fig. 8. In the first case the frequency range is 0.2% and in the second case, this range is increased to 1% which is equivalent to the increasing of the slope of active power – frequency curve. Note that in Figs. 9-a and 9-b, the poles with the same shape are corresponding to a line length. So, increasing of the slop of active power-frequency droop characteristic leads to the dominant poles go away from the imaginary axis and speed up the system response. However, studies have shown that increasing the slope, does not change the length where the instability starts. Fig.9 shows the results of the time domain simulation. The speed up of the system response is clear.

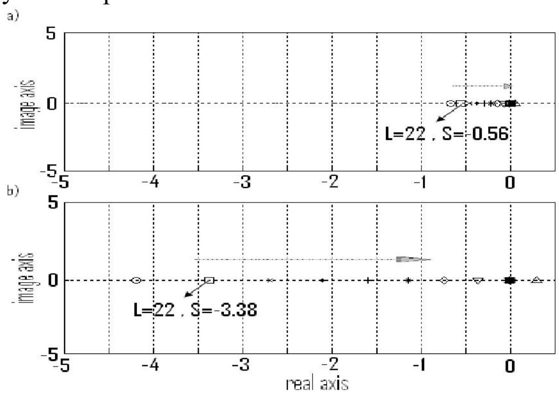

Fig. 8. root locus of the dominant poles of the system in the stability margin during length increases for allowed frequency ranges of. a) 0.2% and b) 1%

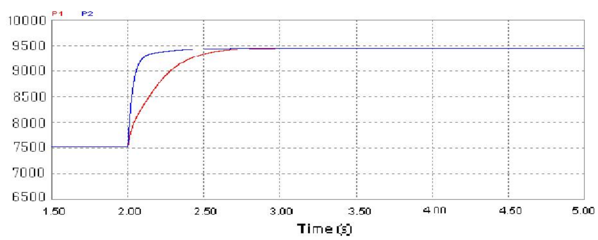

Fig. 9. Time domain simulation for L=22 and allowed frequency range of 1%

As shown, the coupling between active power and power angle (frequency) ,first, is reduced by increasing the length. This causes the system to behave slowly. Now with increasing the slope of active power-frequency we can improve the dynamic system response in deal with the applied disturbance.

In view of the system instability, according to Fig. 2 and attention to this issue that the inherent relationship of the system by changes its sign will cause instability, it can be concluded that the instability can be eliminated by reversing the slope of active power – frequency curve. This conclusion is confirmed by drawing the locus of the effective eigenvalues as shown is in Fig. 10.

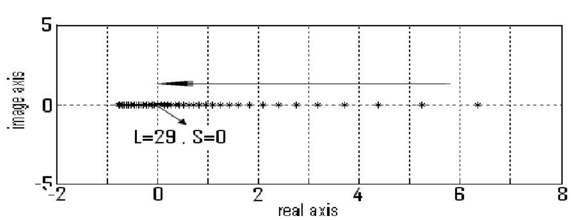

Fig. 10. The root locus of the dominant poles of the system for L=45 and with a positive slope of active power-frequency droop characteristic.

Another method for improving the stability is the change of slope of the reactive power-voltage droop characteristic. Fig. 11 shows the locus of effective eigenvalus of the system with the allowable ranges of voltage measurement (0.02 and 0.05 pu). This increase is equivalent to the increasing of the slope of reactive power–voltage curve. Increasing of the slop of reactive power-voltage droop characteristic leads to increasing the length where the instability starts. Although this improvement has not a great impact on the slow dynamic response of the system is long lines.

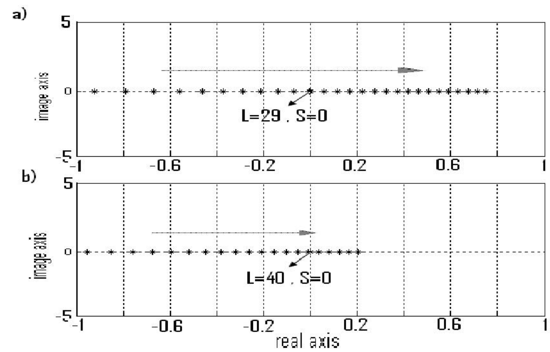

Fig. 11. The root locus of the dominant poles of the system in the stability margin during length increases and voltage ranges. a) 0.02 pu b) 0.05 pu.

As shown in Figs 8 and 11, to improve the system performance, we can change the slops of both the active power-frequency and reactive power-voltage curves. However, the increasing of these slops leads to increase frequency and voltage deviation from the ideal value that cannot be acceptable in some circumstances. To resolve this problem, there is need for a secondary control system which actuates with the frequency and voltage deviation and corrects the permanent values of voltage and frequency by vertical displacement of droop characteristic curves. Use of this method requires some hardware and weak communication links in some cases[15].

4. Conclusion

In this paper, the dynamic model of a Microgrid Lengthening lines is investigated. The main objective of this paper is to illustrate the phenomena which cause instability and verify that by different methods. Derived equations showed attenuation and sign change of coupling between active power and frequency which lead to system instability. MG small signal models and time simulation system also confirm the above conclusion. It is shown that increasing the slope of active power-frequency droop characteristic curve leads to improved system dynamic and reduces the time constant of system response for long lines. Moreover, it is proved that when the slope of reactive power-voltage droop characteristic curve increases the system stability is improved. The platform obtained in this research work and the methodology used can be basically used in all small-signal analysis associated with a MG. In the last section of this paper, corrective measures to retain system stability even with lengthy lines are also discussed.

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