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Feasible Ranges of Microgrid Parameters Based on Small-signal Stability Analysis

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Abstract—The transition from conventional generation to renewable energy sources (RES) motivated the energy sectors to focus on the microgrid (MG) concept. The stable operation of a microgrid is affected by multiple agents and parameters such as controllers, loads, lines, phase locked loop (PLL), and virtual impedances (VI). The virtual impedances (VI) was introduced to correct the impedance mismatches and subsequent performance characteristics in a MG. The effect of VI on MG stability is significant and should be analyzed thoroughly. This paper firstly draws the MG dynamic model including PLL, VI, current feedback coefficient (F) and induction machinery (IM). Then the non-linear dynamic equations are linearized around an operating point. Finally, the eigenvalues analysis is applied to evaluate the small-signal stability of islanded MG while the induction machinery (IM) and ideal resistive-inductive loads are installed at the MG, simultaneously. The permissible intervals for MG parameters are drawn from the MG stability point of view which is a useful procedure to control the MG effectively and inside a stable region of operation.

Index Terms—Islanded microgrid, Virtual impedances, small-signal stability, Induction machinery.

Nomenclature

<i>DG</i>	Distributed Generation
<i>VI</i>	Virtual Impedances
<i>IM</i>	Induction Machinery
<i>MG</i>	Microgrid
<i>PLL</i>	Phase-Locked Loop
<i>RES</i>	Renewable energy sources
<i>THD</i>	Total Harmonic Distortion
<i>ROCOF</i>	Rate of change of frequency
<i>Nadir</i>	Point of minimum frequency
<i>F</i>	current state-feedback factor
<i>LPF</i>	Low-pass filter
<i>PCC</i>	Point of common coupling
<i>PSO</i>	Particle swarm optimization

I. INTRODUCTION

A. Motivation and Background

An islanded microgrid (MG) including virtual impedances (VI), phase locked loop (PLL), and induction machinery (IM) is subjected to instability in the occurrence of small perturbations [12]. Following the recent researches in the field

of MG small-signal stability, this research aims to spotlight applying the IM. This important loads can affect the MG stability considering their dynamic characteristics. The starting behavior of IM and their full-load characteristics are totally different and subsequently critical from the MG stability point of view.

B. Relevant Literature

The small-signal stability of MG has been analyzed in [2] as a milestone for future researches. The application of PLL as a essential element in [3] complemented the previous research and provided a thorough small-signal model for islanded MG. The research in [4] have been devoted to the microgrid stability analysis while supplying both ideal load and drive-interfaced induction motors. The distributed control methods including transmission latency can affect the MG stability as reported by [5]. The application of lead compensators could extend the stability margin of an islanded MG as proposed in [6]. It has been reported that the interaction between MG clusters lowers the MG stability margin and the small-signal model introduced in [7] aim at analyzing the coupling among MG clusters from the stability point of view. The internal model-based controllers in [8] have been applied and modeled in small-signal stability and the MG parameters have been optimized using PSO algorithm. The active power sharing in an hybrid microgrid including both Diesel Generators and power electronic converters could have a major effect on MG stability which has been scrutinized in [9]. The feasible range of virtual impedances considering the node voltage limits and proper reactive power sharing has been drawn in [10] using PSO algorithm. The impedance mismatches among paralleled converters could significantly deteriorate the fair power sharing and MG stability subsequently, the virtual resistance and reactance tuning method in [11] has been proposed to compensate these unwanted coupling effects.

C. Contributions and organization

This study provides the small-signal model of an islanded MG including PLL, VI, and IM. The dynamic modelling is performed on a common dq reference frame. The simultaneous application and modeling of all these participants in MG small-signal analysis has not been found in previous researches

and can be mentioned as the first contribution of this study. Then, the feasible range of virtual resistance and virtual reactances are determined based on small-signal modeling of MG and using MG eigenvalue analysis. The rest of this paper is organized as follows; The small-signal modeling of islanded MG on a common dq reference frame is developed in section II. The small-signal stability analysis of islanded MG is evaluated in section III by eigenvalue analysis. The simulation results are provided in section IV. The final conclusions are drawn in section V.

II. THE ISLAND MICROGRID SMALL-SIGNAL MODELING

An islanded MG includes DG units, load, lines and storage units. However, the storage systems are out of scope of this research. The control block diagram of a converter-interfaced DG is seen in Fig.1. The control blocks should be modeled as a primary task. The complete MG system includes converters, loads and lines which must be modeled afterwards. It is noteworthy that the MG is controlled on a common DQ reference frame; one converter is chosen as the common reference frame and the angle of another local reference frames are measured with respect to this converter. So an angle is drawn for any converter which is feed to the $dq2abc$ conversion blocks in Fig.1.

A. The small-signal modeling of converter-interfaced DG

The control block diagram of a converter-interfaced DG is illustrated in Fig.1. The virtual impedances can correct the reactive behavior of converters while sharing power in a MG and they are considered in the control block-diagram.

1) *Power calculator*: Two dynamic equations describing the power calculator block as seen in Fig.1 are as follows. The instantaneous power components pass from two low pass filters (LPF) with the cut-off frequency of ω_c and yield the active and reactive powers.

$$p = \frac{3}{2}(v_{od} \cdot i_{od} + v_{oq} \cdot i_{oq}) \Rightarrow P = \frac{\omega_c}{s + \omega_c} \cdot p \quad (1)$$

$$q = \frac{3}{2}(v_{od} \cdot i_{oq} - v_{oq} \cdot i_{od}) \Rightarrow Q = \frac{\omega_c}{s + \omega_c} \cdot q \quad (2)$$

2) *Droop control*: The active power droop control is described by Equation.3 which is the traditional droop control equation. ω_0 is the nominal frequency of MG.

$$\omega^* = \omega_0 - m_p \times (P - P_0) \quad (3)$$

3) *Virtual impedances*: The control method aligns the voltage vector towards q-axis and d-axis voltage is forced to zero accordingly. The virtual impedances are considered to correct the reactive power behaviors of converters. The voltage reference points are assigned by following equations:

$$v_{od}^* = 0 \quad (4)$$

$$v_{oq}^* = v_{oq0} - n_q \times (Q - Q_0) - R_v \times i_{oq} - X_v \times i_{od} \quad (5)$$

4) *Voltage controller*: The current set-points are generated based on following dynamic equations in dq reference frame. It should be noted that ϕ_d and ϕ_q are two auxiliary parameters which facilitate the dynamic modeling formulation but they do not introduce any physical meaning.

$$\dot{\phi}_d = \omega_{PLL} - \omega^* \Rightarrow i_{ld}^* = F \cdot i_{od} + k_{iv} \cdot \phi_d + k_{pv} \cdot \dot{\phi}_d \quad (6)$$

$$\dot{\phi}_q = v_{oq}^* - v_{oq} \Rightarrow i_{lq}^* = F \cdot i_{oq} + k_{iv} \cdot \phi_q + k_{pv} \cdot \dot{\phi}_q \quad (7)$$

5) *Current controller*: The voltage set-points in dq reference frame are controlled based on Eq.8 and Eq.9. Again two auxiliary parameters; ϕ_d and ϕ_q ; are used to facilitate the dynamic formulation.

$$\dot{\gamma}_d = i_{ld}^* - i_{ld} \Rightarrow v_{id}^* = -\omega_n \cdot L_f \cdot i_{ld} + k_{ic} \cdot \gamma_d + k_{pc} \cdot \dot{\gamma}_d \quad (8)$$

$$\dot{\gamma}_q = i_{lq}^* - i_{lq} \Rightarrow v_{iq}^* = -\omega_n \cdot L_f \cdot i_{lq} + k_{ic} \cdot \gamma_q + k_{pc} \cdot \dot{\gamma}_q \quad (9)$$

6) *Bus voltage components*: The buses voltages in dq common reference frame are calculated using the virtual resistor method introduced in [2]. The DQ indices refer to common global reference frame.

$$v_{bD} = r_N (i_{od} \pm i_{line_d} - i_{load_d}) \quad (10)$$

$$v_{bQ} = r_N (i_{oq} \pm i_{line_q} - i_{load_q}) \quad (11)$$

The $\pm$ sign is used in the previous equations to denotes the direction of current in line, it means that for a certain direction of line current, it is positive for one bus and it is negative for adjacent bus.

7) *Local to common transformations and vice versa*: The bus voltages for all converters except the reference converter are calculated on common DQ reference frame and they are then translated to local converters dq reference frames using the following transfer equation:

$$\begin{pmatrix} v_{bd} \\ v_{bq} \end{pmatrix} = \begin{pmatrix} \cos(\delta) & \sin(\delta) \\ -\sin(\delta) & \cos(\delta) \end{pmatrix} \begin{pmatrix} v_{bD} \\ v_{bQ} \end{pmatrix} \quad (12)$$

In case of output current components for all converters except the reference converter injected by converters, the calculated values on local reference frames are translated to common global reference frame using following transformation:

$$\begin{pmatrix} i_{oD} \\ i_{oQ} \end{pmatrix} = \begin{pmatrix} \cos(\delta) & -\sin(\delta) \\ \sin(\delta) & \cos(\delta) \end{pmatrix} \begin{pmatrix} i_{od} \\ i_{oq} \end{pmatrix} \quad (13)$$

B. Dynamic modeling of symmetrical induction machinery

A symmetrical induction machinery (IM) is modeled in dq reference frame. The three-phase stator windings are connected to the bus and therefore are supplied by bus voltage. However, the rotor windings are assumed to be short-circuit in low-voltage fixed-speed applications. It is assumed that a low-voltage IM is directly connected to the bus which is reasonable in low-voltage practical applications where using an

Fig. 1. The proposed control method for a converter in an island microgrid.

Fig. 2. The test microgrid.

$$F = - \begin{pmatrix} r_s & \frac{\omega_e}{\omega_b} X_{ss} & 0 \\ -\frac{\omega_e}{\omega_b} X_{ss} & r_s & -\frac{\omega}{\omega_b'} X_M \\ 0 & s_0 \frac{\omega_e}{\omega_b} X_M & r_r' \\ -s_0 \frac{\omega_e}{\omega_b'} X_M & 0 & -s_0 \frac{\omega_e}{\omega_b} X_{rr}' \\ X_M i_{dr0}' & -X_M i_{qr0}' & -X_M i_{ds0} \\ \frac{\omega_e}{\omega_b} X_M & 0 & 0 \\ 0 & 0 & 0 \\ s_0 \frac{\omega_e}{\omega_b'} X_{rr}' & -X_M i_{ds0} - X_{rr}' i_{dr0}' & 0 \\ r_r & X_M i_{qs0} + X_{rr}' i_{qr0}' & 0 \\ X_M i_{qs0} & 0 & 0 \end{pmatrix} \quad (16)$$

$$U = \begin{pmatrix} \Delta v_{qs} \\ \Delta v_{ds} \\ \Delta v_{qr}' \\ \Delta v_{dr}' \\ \Delta T_L \end{pmatrix} \quad (17)$$

interface device is not usual. The following state variables are considered for the IM and corresponding dynamic equations are linearized around an stable operating point:

Five state variables are chosen to model the IM in dq reference frame as follows: $x_{IM} = \{i_{qs}, i_{ds}, i_{qr}', i_{dr}', \omega_r\}$;

$$E \cdot \Delta \dot{x}_{IM} = F \cdot \Delta x_{IM} + U \quad (14)$$

$$E = \frac{1}{\omega_b} \begin{pmatrix} X_{ss} & 0 & X_M & 0 & 0 \\ 0 & X_{ss} & 0 & X_M & 0 \\ X_M & 0 & X_{rr}' & 0 & 0 \\ 0 & X_M & 0 & X_{rr}' & 0 \\ 0 & 0 & 0 & 0 & -2H\omega_b \end{pmatrix} \quad (15)$$

Where r_s , r_r' , ω_e , X_{ss} , X_{rr}' , X_M , s_0 are stator winding resistance, rotor winding resistance (transferred to the stator side), the local reference frame speed, the stator winding reactance, the rotor winding reactance (transferred to the stator side), the mutual linkage reactance and the rotor slip respectively. The rotor slip in the nominal operating point will be a small positive value near zero which is calculated as

follows:

$$s_0 = \frac{\omega_e - \omega_{r0}}{\omega_e} \quad (18)$$

As the IM is installed on a bus in a MG, the voltage perturbations could be calculated based on the virtual resistor method introduced in [3] as follows:

$$\Delta v_{ds} = r_N \times (\Delta i_{oD} \pm \Delta i_{lineD} - \Delta i_{ds}) \quad (19)$$

$$\Delta v_{qs} = r_N \times (\Delta i_{oQ} \pm \Delta i_{lineQ} - \Delta i_{qs}) \quad (20)$$

The squirrel cage IM is modeled so the rotor windings are short-circuit connected ($\Delta v'_{qr} = 0$, $\Delta v'_{dr} = 0$). The D and Q indices are used to annotate the values on common dq reference frame. The thorough description of the $dq2DQ$ conversion can be found in relevant literature [2]- [3].

C. The microgrid eigenvalues analysis

An islanded MG as a dynamical system is asymptotically stable if the whole eigenvalues of it except one locate in left-hand side of complex plain [12]. The non-linear dynamic equations of MG should be linearized around an stable operating point and then an eigenvalues analysis can be an effective measure to evaluate the MG stability. The *eig* command in MATLAB could be useful to draw the eigenvalues of the MG.

$$x = [\Delta \delta_1, \Delta P_1, \Delta Q_1, \Delta \varphi_{d1}, \Delta \varphi_{q1}, \Delta \gamma_{d1}, \Delta \gamma_{q1}, \Delta i_{ld1}, \Delta i_{lq1}, \Delta v_{od1}, \Delta v_{oq1}, \Delta i_{od1}, \Delta i_{oq1}, \Delta \varphi_{PLL1}, \Delta v_{odf1}, \Delta \delta_2, \Delta P_2, \Delta Q_2, \Delta \varphi_{d2}, \Delta \varphi_{q2}, \Delta \gamma_{d2}, \Delta \gamma_{q2}, \Delta i_{ld2}, \Delta i_{lq2}, \Delta v_{od2}, \Delta v_{oq2}, \Delta i_{od2}, \Delta i_{oq2}, \Delta \varphi_{PLL2}, \Delta v_{odf2}, \Delta i_{loadd1}, \Delta i_{loadq1}, \Delta i_{ds}, \Delta i_{qs}, \Delta i_{linea}, \Delta i_{lineq}, \Delta i'_{qr}, \Delta i'_{dr}, \Delta \omega_r]$$

for any state variable mentioned above, the previous equations (Equations.1-21) are used and any dynamic equation is linearized around the MG operating point. It is noteworthy that the first order terms are considered in the Taylor series while linearizing.

$$\dot{x} = Ax \quad (21)$$

III. SIMULATION RESULTS

A 2-Bus MG introduced in [3] was used to examine the proposed small-signal stability analysis and to draw the feasible range of the MG parameters which is an important aspect of MG stability and control. The full-specifications of MG are listed in Table.I. An IM is installed in bus 2 which is a 1 hp low voltage IM and its parameters are assigned in Table.II. The eigenvalues analysis is applied while each parameter is changing in a certain interval and the MG stability is assured while keeping the eigenvalues in left-half plain. As the dynamical equations of the MG are non-linear, a linearization around the working point is done. The operating point is x_0 as follows.

Fig. 3. Active power droop coefficient effect on MG eigenvalues.

$$x_0 = [0, 819.41, 0.007, 0.077, 0.008, 0.879, 1.747, 6.448, 0.001, 84.717, 2.225, 6.448, -0.409, 0.001, 0.001, 819.330, 334.908, 0.012, 0.077, 0.01, 0.878, 2.159, 6.45, 0.0002, 84.665, 2.637, 6.451, -0.409, 0.0002, 1.170, 6.479, 6.090, 3.675, 1.052, -0.199, -6.236, -0.684, 352.286]$$

Once the linearization of MG dynamic equations is done and the A matrix is known, then an eigenvalue analysis using *eig(A)* command in MATLAB is performed to demonstrate the eigenvalues locus.

A. Active power droop coefficient

The active power droop coefficient is effective on microgrid small-signal stability. Fig.3 demonstrates the major eigenvalues of the test MG while the droop coefficient is changing from 0 to 1. As it is seen at $m = 0.487$ two branches of eigenvalues enter the right-half plain and the MG becomes unstable subsequently. The MG controller could choose any value in between $0 < m < 0.487$ based on the control strategy and the objective function of the MG.

B. Reactive power droop coefficient

The reactive power droop coefficient is another major parameter contributing to the MG stability. The dominant eigenvalues of the test MG are drawn in Fig.4 while the reactive power droop coefficient is changing from 0 to 1. It is seen that the reactive power coefficient could change in a limit interval from 0 to 0.017 to keep the MG eigenvalues in left half plain of complex plain which is known to be the asymptotically stable region because the MG has one zero eigenvalue.

C. Virtual inductances of converters

Virtual impedances which are applied to correct the reactive power behavior of converters while sharing power in a MG. The major eigenvalues of MG are drawn and depicted in Fig. 5 and Fig. 6 while the virtual inductance of converter 1 and converter 2 are changed from 0 to 1, respectively. It is seen in these figures that the maximum permissible value for Lv_1 and Lv_2 are 17 mH and 67 mH respectively.

Fig. 4. Reactive power droop coefficient effect on MG eigenvalues.

Fig. 5. The virtual inductance of converter 1 effect on MG eigenvalues.

D. Virtual resistances of converters

The virtual resistances can affect the MG small-signal stability as it is seen in Fig.7 and Fig.8. Increasing either R_{v1} or R_{v2} propels the eigenvalues towards the left-half of the complex plain. It is seen that choosing virtual resistances in an interval identical to those corresponding inductances could keep the MG stable and the eigenvalues stay in left-half plain while R_{v1} or R_{v2} is set at a value ranging from 0 to 1.

E. The filter inductance (L_f)

The interface inductance of filter is another participant of small-signal stability analysis which can change in a certain interval to keep the MG stable. As it is seen in Fig.9, while increasing the filtering inductance the dominant eigenvalues move towards right-hand half plain which can be seen as unstable region of MG. As it is seen in Fig.9, maximum permissible value for the filtering inductance is 31 mH from the stability point of view. Apparently, the preferred THD requires a certain amount of inductor and capacitor which is another criteria and it is out of scope of this study.

F. The damping resistance (R_d)

The damping resistance in series with the filter capacitor could displace the critical eigenvalues and it can be set accordingly to enhance the MG small-signal stability. As it is seen in Fig.10, decreasing the damping resistance pushes the dominant eigenvalues towards right hand half plain which is equivalent to the unstable operation of MG. According to Fig.10 minimum permissible value for the damping resistance in the simulated MG is 0.133 Ω from the stability point of view. Apparently choosing a smaller inductor cause the MG to operate in unstable region.

Fig. 6. The virtual inductance of converter 2 effect on MG eigenvalues.

Fig. 7. The virtual resistance of converter 1 effect on MG eigenvalues.

G. The current state-feedback factor

One important participant of MG small-signal stability is the current state-feedback factor (F) which can change in an interval based on small-signal stability analysis. Fig.9 demonstrates the dominant eigenvalues of MG while the current state-feedback factor (F) is changing from 0 to 1. It is seen that the maximum permissible value of F is 0.67 to keep the MG stable. One important point is that while increasing F two different trends are seen in Fig.9; firstly the eigenvalues are pushed towards left and then after a certain point the trends is reversed which means increasing F propels the eigenvalues towards right-half plain.

TABLE I
FULL SPECIFICATIONS OF CONTROLLERS AND THE MICROGRID.

Parameter	Value	Parameter	Value
L_f	4.2 mH	r_f	0.50 Ω
L_c	0.5 mH	r_c	0.09 Ω
C_f	15 μF	R_d	2.025 Ω
ω_c	50.26 rad/s	ω_n	377 rad/s
$\omega_{c,PLL}$	7853.98 rad/s	ω_{PLL}	377 rad/s
m	0.001 rad/Ws	n	0.001 V/Var
r_N	1000 Ω	V_{oqn}	85.0 V
R_{load1}	25 Ω	L_{load1}	15 mH
R_{pert1}	25 Ω	L_{pert1}	7.5 mH
R_{line}	0.15 Ω	L_{line}	0.4 mH
v_{bD1}	0 V	V_{bQ1}	85 V
v_{bD2}	0 V	V_{bQ2}	85 V
k_{ppl}	0.25	k_{ipll}	2
k_{pv}	0.5	k_{iv}	25
k_{pc}	1	k_{ic}	100

Fig. 8. The virtual resistance of converter 2 effect on MG small-signal stability

Fig. 9. The filter inductance effect on MG eigenvalues.

IV. CONCLUSIONS

A comprehensive small-signal modeling of an islanded microgrid in dq reference frame was presented which includes phase-locked loop, normal resistive-inductive loads and induction motors and lines. The corresponding state-space equations are nonlinear and hence are linearized around an stable operating point so as the state matrix (A) is drawn as a square matrix including constant entries. The eigenvalues analysis was applied to measure the stability of the MG as a dynamic system. The operating point was around the nominal speed of IM and the nominal point of other load. The feasible range of control parameters, damping resistor, current state feedback coefficient, virtual impedances, the filtering inductances and droop coefficients from the stability point of view were analysed as the main contribution of this study. These parameters are tuned based on the objective of the microgrid control strategy.

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TABLE II
FULL SPECIFICATIONS OF INDUCTION MOTOR.

Parameter	Value	Parameter	Value
Nominal power	1 hp	T_B	3.966 N.m
Nominal voltage	85 V	J	0.089 kg.m ²
Nominal speed	1710 rpm	r_s	0.435 Ω
X_{ls}	50.26 Ω	X_M	26.13 Ω
X'_{lr}	0.754 Ω	r_r	0.816 Ω

Fig. 10. The damping resistance effect on MG eigenvalues.

Fig. 11. The current state-feedback factor effect on MG eigenvalues.

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