Modelling of a renewable energy-based AC interconnected rural microgrid system for the provision of uninterrupted power supply

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Abstract
A stability study of interconnected microgrids is presented herein. This interconnection is vital to enhance the performance under dynamic conditions by providing mutual power support. The microgrids considered are based on three renewable energy sources, namely wind, solar, and biogas. The wind energy converting system (WECS) considered has a permanent magnet synchronous generator (PMSG) for conversion to electrical energy. A solar photovoltaic system (SPVS) with appropriate inverter has been incorporated. These two renewable energy sources are intermittent in nature. A biogas genset (BG) consisting of a biogas engine coupled with a synchronous generator is the third power source. The interconnection is by an AC line. Two interconnected microgrids, M1 and M2, are considered for mathematical modelling. Additionally, the microgrid M2 is also connected to the main grid for a limited but continuous power supply. Proportional integral (PI) controllers are used to control the frequency and voltage of the microgrids. Simulation studies are conducted on the system under step load disturbances and also for step changes in input power of wind/solar. It has been found that frequency and voltage deviations of the microgrids vanish under steady-state conditions.

1 | INTRODUCTION

In recent times, a rapid growth in renewable energy (RE) sources has been witnessed across the world due to rising concerns about environmental loadings (specifically CO2). Consequently, many problems in the area of renewable integration to grids have been identified in the literature and many solutions have also been proposed to the identified problems. Major characteristics that possess challenges for integration of RE sources are:

- **Intermittent availability** of the input source, which makes the power output highly intermittent and unreliable in nature.
- **Low flux density**, that is, they require larger areas per unit power generation in contrast to conventional generators.
- **Low inertia**, RE sources, such as PV and WECS, have lower inertia when compared to conventional sources, which reduces the grid's ability to handle frequency deviation on its own.

In the literature, various combinations of RE sources and their characteristics have been studied. The stability of microgrids is an important area of concern. Some of the aspects of microgrids have been studied and presented by various authors in the literature [1]. Sustained low-frequency oscillations are one of the problems in microgrids, as discussed in [2–4]. The other problem is voltage control of the microgrid system [5, 6]. There is literature available in which these problems are treated independently as well as together. A microgrid comprising of solar and wind requires backup due to its intermittent nature. Inverter connected battery backup is one of the solutions as deliberated in [7, 8]. The other solution is provision of a diesel/biogas-based generating plant [9]. Various control architectures are proposed in a wind–solar–diesel-based system using different optimising techniques [10–12]. Studies have been carried out on AC and DC microgrids [13, 14]. The system studies mainly are comprised of simulation based on power flow model, primary droop control, secondary current-sharing control, etc. [15–17]. To maintain dynamic stability, fast controllers are required.
Therefore, a bidirectional communication system between the controller and devices forms an important aspect [18–20]. Apart from stability studies, the feasibility studies of microgrids include techno-commercial analysis [21, 22]. Renewable energy sources are major components of these microgrids. Therefore, frequency dynamics is a very crucial task due to the high penetration of these renewable sources and their intermittent nature [23]. Voltage deviation is another aspect which occurs due to switching of industrial loads comprising of induction motor, reduction in generation from renewable energy sources, and large disturbances. Therefore, it is important to track voltage deviation and mitigate the same at the earliest opportunity to prevent high losses, reduction in efficiencies of the loads, and voltage collapses at extreme conditions [24].

A solar–wind-based system needs to be backed by additional sources due to uncertainty depending on prevailing environmental conditions, with a day/night scenario [25, 26]. Also, the rate of generation change in SPVS is very fast due to cloud transient [27]. The PV unit of the SPVS is integrated into the power system through an inverter; therefore, control of the PV plant is dominated by control of the inverter [28].

According to the aerodynamic properties, the power output of the wind turbine is proportional to the square of the rotor diameter and a cubic of the wind speed [29]. The generator and converters are two important electrical constituents of WECS with fixed type or variable type arrangement located onshore or offshore [30]. However, considering various factors, a variable-speed wind turbine with back-to-back converter is one of the configurations being widely used [31]. An induction generator (IG) and permanent magnet synchronous generator (PMSG) are mainly used in WECS. However, the IG requires reactive power compensation to produce the required active power [32]. The PMSG is an alternative to IG as it is robust and does not require separate excitation control [33]. SPVS and WECS are connected to the system through power inverters. Also, the associated inverter provides virtual inertia to the system [34]. There is literature in which it is stated that emulated inertia of WECS- and SPVS-based inverters can approximately behave as conventional generators, which can be used for dynamic stability of the power system. However, an energy buffer needs to be reserved [35].

For a low-power system unlike SPVS and WECS, biogas genset (BG) and diesel genset can be used as the controlled source, as the fuel input BG-based genset can be controlled. Study of a PV–diesel hybrid system with energy storage has been carried out for frequency control in an isolated system [36]. In one study, power flow models were proposed for WECS with biogas and a limited grid for studying the dynamic stability of the system [37]. Biogas/diesel gensets are generally accompanied with a synchronous generator. The speed governor control and automatic voltage regulator help in controlling frequency and voltage, respectively [38]. Various types of excitation control for a synchronous generator are presented for stability study [39]. The dynamic stability of a wind–solar–biogas–grid connected system with STATCOM has been carried out with the objective of mitigating frequency and voltage oscillation subjected to load disturbance [40].

The rural electrification has greatly progressed in the last decade. In developing countries electrification has been achieved but 24 × 7 continuous power supplies remain a problem. These areas still suffer from power-cuts from time to time. The main reasons for disturbed power supplies are deprived grid connection, dependency on conventional generation, weak power infrastructure, long-distance transmission, and importance to urban and industrial areas [41]. From the literature review, it can be observed that various arrangements of microgrids have been presented by the authors. However, to create a self-sufficient village integrated and interconnected supply system with 24 × 7 power availability based on load segregation and setting the priority loads has not been considered. Herein, a stability study of interconnected microgrids has been presented in order to observe the system dynamics while sharing the power between two microgrids for ensuring uninterrupted power supply. This model has been developed considering realistic rural generation availability and is tested with a typical scenario. The major contributions of the work carried out are:

- System modelling as well as integrating renewable energy sources considering power sharing between the generating sources.
- Optimum tuning of controllers for mitigating frequency and voltage oscillation.
- Interconnecting microgrids through LVAC network.
- Load segregation and priority load setting to meet the conception of uninterrupted power supply.
- Control of frequency and voltage oscillation within 5 s as desired.

In Section 2, the modelling of the interconnected microgrid system is explained. The mathematical modelling of the individual components and the system is presented in Section 3, and a case study of eight medium-sized villages is outlined in Section 4. The results and discussions are given in Section 5. Finally, the proposed work is concluded in Section 6.

2 | MATHEMATICAL MODELLING

2.1 | Modelling of the system

The interconnected system is modelled considering a case wherein microgrid M1 has a surplus power of 50 kW, which is transferred to the microgrid M2. At steady state, the power transferred through the interconnection remains the same at all conditions. Any change in demand or generation is taken care of locally by the respective microgrid systems. The single-line diagram (SLD) of the interconnected microgrid system is presented in Figure 1.

At steady state, real and reactive power balance can be expressed by Equations (1) and (2):

\[ P_{LD} = P_W + P_G + P_{PVS} + P_{BG} \pm P_{IC} \]  \( (1) \)
\[ Q_{LD} = Q_W + Q_G + Q_{PVS} + Q_{BG} \pm Q_{IC} \] (2)

For a small disturbance in power flows, Equations (1) and (2) can be written as:

\[ \Delta P_{LD} = \Delta P_W + \Delta P_G + \Delta P_{PVS} + \Delta P_{BG} \pm \Delta P_{IC} \] (3)
\[ \Delta Q_{LD} = \Delta Q_W + \Delta Q_G + \Delta Q_{PVS} + \Delta Q_{BG} \pm \Delta Q_{IC} \] (4)

A change in real power demand/generation would result in a change in frequency of the system, which in the Laplace domain can be given as:

\[ \Delta F(s) = \frac{K_{FS}}{1 + s \cdot T_{FS}} (\Delta P_W + \Delta P_G + \Delta P_{PVS} + \Delta P_{BG} \pm \Delta P_{IC} - \Delta P_{LD}) \] (5)

Similarly, a change in reactive power mismatch results in a change of system bus voltage given by:

\[ \Delta V(s) = \frac{K_{VS}}{1 + s \cdot T_{VS}} (\Delta Q_W + \Delta Q_G + \Delta Q_{PVS} + \Delta Q_{BG} \pm \Delta Q_{IC} - \Delta Q_{LD}) \] (6)

3 | Modelling of the components

3.1 | Modelling of WECS with PMSG

A permanent magnet synchronous generator-based wind turbine is considered for WECS, which is further connected to the common bus through AC/DC/AC power electronic interface and transformer. The single-line diagram is shown in Figure 2.

The real and reactive power flow equations similar to synchronous generator with internal reactance \( X_{TWS} \) are given by [37]:

\[ P_W = \frac{V_{inW} \times V \times \sin(\delta_{inW} + \theta)}{X_{TWS}} \] (7)
\[ Q_W = \frac{V_{inW} \times V \times \cos(\delta_{inW} + \theta) - V^2}{X_{TWS}} \] (8)

A small perturbation in power flows can be expressed in the Laplace domain as:

\[ \Delta P_W(s) = K_{W1} \Delta V_{inW} (s) + K_{W2} \Delta V(s) \]
\[ + K_{W3} \delta_{inW}(s) + K_{W4} \Delta \theta(s) \] (9)
\[ \Delta Q_W(s) = K_{W5} \Delta V_{inW} (s) + K_{W6} \Delta V(s) \]
\[ + K_{W7} \delta_{inW}(s) + K_{W8} \Delta \theta(s) \] (10)

where
The delay due to inertia of the system has been accounted as:

\[
\Delta P_W(s) = \frac{1}{1 + sT_W} \Delta P_W'(s) \quad (11)
\]

\[
\Delta Q_W(s) = \frac{1}{1 + sT_W} \Delta Q_W'(s) \quad (12)
\]

Using Equations (9)–(12), the transfer function block diagram of WECS can be constructed as shown in Figure 3.

### 3.2 Modelling of a solar PV system with an inverter (SPVS)

Power obtained from a PV panel is DC. Hence, before coupling with the common bus, the power obtained is passed through a DC/DC/AC power electronic interface, which is further connected to a common bus through a transformer. The single-line diagram is shown in Figure 4.

Similar to WECS, the power equations considering \(X_{TPV}\) as internal reactance are given by

\[
P_{PV} = V_{inPV} \times V \times \sin(\delta_{inPV} + \theta) \quad (13)
\]

\[
Q_{PV} = V_{inPV} \times V \times \cos(\delta_{inPV} + \theta) - V^2 \quad (14)
\]

For a small perturbation, Equations (13) and (14) can be written in the Laplace domain as:

\[
\Delta P'_{PV}(s) = K_{PV1} \Delta V_{inPV}(s) + K_{PV2} \Delta V(s) + K_{PV3} \Delta \delta_{inPV}(s) + K_{PV4} \Delta \theta(s)
\]

\[
\Delta Q'_{PV}(s) = K_{PV5} \Delta V_{inPV}(s) + K_{PV6} \Delta V(s) + K_{PV7} \Delta \delta_{inPV}(s) + K_{PV8} \Delta \theta(s)
\]

where

\[
K_{PV1} = \frac{\partial P_{PV}}{\partial V_{inPV}} \quad K_{PV2} = \frac{\partial P_{PV}}{\partial V} \quad K_{PV3} = \frac{\partial P_{PV}}{\partial \delta_{inPV}}
\]

\[
K_{PV4} = \frac{\partial Q_{PV}}{\partial \delta_{inPV}} \quad K_{PV5} = \frac{\partial Q_{PV}}{\partial V_{inPV}} \quad K_{PV6} = \frac{\partial Q_{PV}}{\partial V}
\]

\[
K_{PV7} = \frac{\partial Q_{PV}}{\partial \delta_{inPV}} \quad K_{PV8} = \frac{\partial Q_{PV}}{\partial \theta}
\]

The delay due to inertia of the system can be accounted as:

\[
\Delta P_{PV}(s) = \frac{1}{1 + sT_{PV}} \Delta P'_{PV}(s) \quad (17)
\]

\[
\Delta Q_{PV}(s) = \frac{1}{1 + sT_{PV}} \Delta Q'_{PV}(s) \quad (18)
\]

Using Equations (15)–(18), the transfer function block diagram of SPVS can be constructed as shown in Figure 5.

### 3.3 Modelling of BG

The BG model has been adopted from [40]. The transfer function block diagram of a real power generation model and reactive power generation model are shown in Figure 6(a) and (b).
The real power generation block diagram considers the electronic speed governor, actuator, and engine/generator. An IEEE type-1 excitation system has been considered for the voltage-reactive power control. The reactive power control in biogas is done by the voltage regulation action of AVR and exciter (Figure 7).

Considering dynamic state after neglecting saturation function, the equations for real and reactive powers are derived and given by:

\[
\Delta E_{qB}(s) = \frac{1}{1 + sT_B} \left[ K_{1B} \Delta E_{fAB}(s) + K_{2B} \Delta V(s) \right] \quad (19)
\]

\[
\Delta Q_B(\Delta Q_B(s) = K_{3B} \Delta E_{qB}(s) + K_{4B} \Delta V(s) \quad (20)
\]

where

\[
T_B = \frac{T_{d}'}{X_d} \quad K_{1B} = \frac{X_d'}{X_d} \quad K_{2B} = \frac{(X_d - X_d') \cos (\delta + \theta)}{X_d}
\]

\[
K_{3B} = \frac{V \cos (\delta + \theta)}{X_d'} \quad K_{4B} = \frac{E_{qB} \cos (\delta + \theta) - 2V}{X_d'}
\]

### 3.4 Modelling of power-controlled grid

A power-controlled grid is a concept wherein the power supplied by the grid remains constant throughout the time period. It has been done by keeping the energy supplied per day unchanged, but with a reduced but constant and continuous power supply.

\[
P_G = \frac{E_G \sin(\theta)}{X_G} \quad (21)
\]

\[
Q_G = \frac{E_G \cos(\theta) - V^2}{X_G} \quad (22)
\]

Following a perturbation, Equations (21) and (22) can be written as:

\[
\Delta P_G(s) = K_{1G} \Delta \theta(s) + K_{2G} \Delta V(s) \quad (23)
\]
\[ \Delta Q_G(s) = K_3G \Delta \theta(s) + K_4G \Delta V(s) \]  \hspace{1cm} (24)

\[ \Delta Q_{IC}(s) = K_4 \Delta V_1(s) + K_5 \Delta V_2(s) + K_6 \Delta \phi_{12}(s) \]  \hspace{1cm} (28)

where

\[ K_{1G} = \frac{\partial P_G}{\partial \theta} \quad K_{2G} = \frac{\partial P_G}{\partial V} \]

\[ K_{3G} = \frac{\partial Q_G}{\partial \theta} \quad K_{4G} = \frac{\partial Q_G}{\partial V} \]

3.5 | Modelling of AC interconnection

An AC short transmission line has been considered while modelling the interconnection. It has a very high \( R/X \) ratio; thus, the line cannot be considered as lossless. The power flow through such a line is given by:

\[ P_{IC} = \frac{V_1 V_2}{Z} \cos(\theta_z - \phi_{12}) - \frac{V_2^2 R_z}{Z^2} \]  \hspace{1cm} (25)

\[ Q_{IC} = \frac{V_1 V_2}{Z} \sin(\theta_z - \phi_{12}) - \frac{V_2^2 X}{Z^2} \]  \hspace{1cm} (26)

where \( \theta_z \) is the angle between \( R_z \) and \( X \) of the line and \( \phi_{12} \) is the difference of voltage angles between bus 1 and bus 2.

For a small perturbation, Equations (25) and (26) in the Laplace domain can be written as:

\[ \Delta P_{IC}(s) = K_1 \Delta V_1(s) + K_2 \Delta V_2(s) + K_3 \Delta \phi_{12}(s) \]  \hspace{1cm} (27)

\[ \Delta Q_{IC}(s) = K_4 \Delta V_1(s) + K_5 \Delta V_2(s) + K_6 \Delta \phi_{12}(s) \]

where

\[ K_1 = \frac{\partial P_{IC}}{\partial V_1} \quad K_2 = \frac{\partial P_{IC}}{\partial V_2} \quad K_3 = \frac{\partial P_{IC}}{\partial \phi_{12}} \]

\[ K_4 = \frac{\partial Q_{IC}}{\partial V_1} \quad K_5 = \frac{\partial Q_{IC}}{\partial V_2} \quad K_6 = \frac{\partial Q_{IC}}{\partial \phi_{12}} \]

The microgrids are modelled using the above individual models of sources.

4 | TEST SYSTEM

Composition of power sources of both the microgrids are shown in Figure 7. The data of the test system for microgrid M2 has been adopted from [40]. The test system data for M2 has been slightly modified to obtain the composition of M1. M2 has been modelled for a cluster of four medium-sized villages having a total contract demand of 1600 kW. The maximum diversified demand taken for M2 is 1000 kW (approx.), 50 Hz, and a nominal voltage of the system of 1 pu. M1 has been modelled considering a cluster of two small and two medium-sized villages. M1 has a rated generation capacity of 1150 kW and maximum diversified demand of 700 kW, 50 Hz, and nominal voltage of 1 pu. The steady-state generation parameters of both microgrids are given in Table 1.
constant power of 50 kW is supplied from the M1 microgrid and after losses 40.6 kW is supplied to the M2 microgrid via an AC interconnection.

The decomposition of the lumped loads in each microgrid is presented in Table 2. Herein, the uninterrupted power supply is associated with high-priority loads rather than the entire system load. Total demand, power flow from AC interconnection, and generation from all the resources in M1 and M2 are listed in Table 3. A negative sign in power flow through AC interconnection in M1 indicates an outflow from the microgrid, whereas a positive sign represents an inward flow of power as in the case of M2. It can be observed that the outflow and inflow of power through the AC interconnection are not equal in both microgrids. This is because of losses in the AC interconnection. A power balance at steady state can be observed locally as well as a whole being observed from Table 3.

| TABLE 2 Composition of loads with their priorities |
|-----------------------------------------------|
| Microgrid | M1 | | M2 | |
| S. No. | Type of Load | Qty | Unit Rating | Total Rating | Priority Type | Qty | Unit Rating | Total Rating | Priority Type |
| a | Household | 850 | 1 kW | 850 kW | High | 500 | 1 kW | 500 kW | High |
| b | Agriculture pump | 5 | 10 kW | 50 kW | Medium | 5 | 5 kW | 25 kW | Medium |
| c | Streetlights | 200 | 50 W | 10 kW | Low | 150 | 50 W | 7.5 kW | Low |
| d | Village administrative block | 4 | 10 kW | 40 kW | Low | – | – | – | – |
| e | Dispensary | – | – | – | – | 1 | 20 kW | 20 kW | High |
| f | Very small industries and commercial complex | – | – | – | – | 97.5 kW | Low |

| TABLE 3 Energy balance at steady state in both microgrids |
|-----------------------------------------------|
| Microgrid | M2 | Microgrid M1 |
| Local load (kW) | 1000 | 650 |
| Total generation (kW) | 959.4 | 700 |
| AC interconnection (kW) | 40.6 | –50 |

5 | SIMULATIONS AND RESULTS

The data of the system considered for simulation studies is given in the Appendix. The PI controllers are tuned using ISE criteria and the tuned values are given in Table 4.

The interconnected system has been simulated for an increase in real and reactive power demand in both microgrids by 0.01 pu each. It has been observed that the PI control is adequate to mitigate the steady-state error in frequency and voltage caused by step disturbances of real power in the interconnected microgrids.

The changes in frequencies and voltages of microgrids M1 and M2 are shown in Figures 8(a) and (b), respectively. It can be observed that following the disturbance, changes in frequencies settle within 4 s and changes in voltages settle within 5 s. A faster settling time as well as lower magnitudes of overshoots/undershoots in frequencies indicate a faster restoration of power–demand imbalances, that is, restoration of kinetic energy of the rotating electrical machines in the system.

The dynamic time responses of the change in real and reactive power flow in AC interconnection and power supply from the grid are presented in Figure 9(a) and (b) respectively. It can be observed that all the parameters settle with zero steady-state error within 4 s. It should be noted that the power flow in the interconnection as well as power supply from the grid are controlled using PI controllers. Hence, following a disturbance, there is a zero steady-state change in the relevant power flows.

The dynamic time responses of the power supply from biogas gensets and the angles \( \theta \) in both microgrids M1 and M2 in Figure 10(a) and (b). \( \theta_1 \) is the reference voltage angle of M1, and \( \theta_2 \) is the reference voltage angle in M2. It can be observed that change in real power in demand is being supplied by the biogas gensets. It can also be inferred from the power sources considered in microgrids, that biogas genset and grid are the resources with slower response times, due to which the settling times of \( \theta \) and biogas active power output are almost the same.

The dynamic time response of change in active powers of WECS and SPVS for the microgrids, M1 and M2 has been shown in the Figure 11. It can be observed that both resources settle in about 2–2.5 s with zero steady-state error.

The dynamic time response of the change in reactive power from the inverters connected in WECS, SPVS, and BG in both microgrids, M1 and M2, respectively, is shown in
Figure 12(a) and (b). Here, the cumulative reactive power generated by the inverters connected in the WECS and PV has been represented by $Q$. There is an increase in reactive power generation from BGs due to the fact that they are designed to operate at a constant power factor of 0.9 lagging and there is an increase in real power generation by 0.01 pu to compensate the increment in active power demand. Hence, BGs generate 0.01 × 0.484 pu reactive power. To maintain reactive power balance, inverters in both microgrids generate the excess reactive power required which can be observed in Figures 12(a) and (b).

6 CONCLUSIONS

In developing countries, there is a tremendous increase in electricity demand as well as for clean but intermittent sources of energy. Consequently, the provision of continuous and uninterrupted supply of power is a major challenge. The modelling of microgrids has been presented to mitigate this problem. Two different clusters of villages were considered, one without grid support and the other with grid support which are represented by microgrids M1 and M2, respectively. These two microgrids have been interconnected by an
AC short transmission line. It has been considered that the excess power generated in M2 is transferred to M1 to ensure continuous power supply in a cluster of villages represented by M2. The microgrids M1 and M2 contain PV, WECS, and biogas genset as renewable energy sources. It has been observed that any disturbance of real power demand occurring in microgrids is compensated by the biogas genset. It has also been found that any dynamic changes in PV and WECS real power generation are compensated by biogas genset. The change in reactive power in the system has been found to be compensated by the reactive power generated by inverters coupled with PV and WECS of individual microgrids. The voltages and frequencies of both microgrids fluctuate within the permissible limits and then settle with zero steady-state error following a disturbance within 5 s, which validates the technical feasibility of the model.

**NOMENCLATURE**

- $P_{LD}, Q_{LD}$: Active and reactive power demand, respectively
- $P_{W}, Q_{W}$: Active and reactive power generation from WECS, respectively
- $P_{G}, Q_{G}$: Active and reactive power supply from grid, respectively
- $P_{PV}, Q_{PV}$: Active and reactive power supply from a photovoltaic system, respectively
- $P_{BG}, Q_{BG}$: Active and reactive power supply from biogas genset, respectively
- $P_{IC}, Q_{IC}$: Active and reactive power inflow through interconnection to the microgrid, respectively
- $K_{FS}, T_{FS}$: Gain and time constants of the system real power, respectively
- $K_{VS}, T_{VS}$: Gain and time constants of the system reactive power, respectively
- $D_{FS}, D_{VS}$: Damping coefficient of real and reactive power, respectively
- $T_{wS}, T_{PVS}$: Time constants of the WECS and SPV systems, respectively
- $X_{TWS}, X_{TPV}$: Thevenin equivalent reactance of WECS and SPV, respectively
- $X_d, X'_d$:
- $T'_{d0}$: Direct axis synchronous reactance and transient reactance of the alternator, respectively
- $T_{d0}$: Direct axis open-circuit transient time constant

**FIGURE 11** (a) $\Delta P_{PV1}$ (pu) versus time, (b) $\Delta P_{PV2}$ (pu) versus time, (c) $\Delta P_{WS1}$ (pu) versus time, (d) $\Delta P_{WS2}$ (pu) versus time

**FIGURE 12** (a) $\Delta Q_{R1}$ (pu) and $\Delta Q_{BG1}$ (pu) versus time, (b) $\Delta Q_{R2}$ (pu) and $\Delta Q_{BG2}$ (pu) versus time
$T_{B1}, T_{B2}$: Time constants of speed governor, actuator, and engine.

$T_{B3}, T_{B4}$: Voltage regulator time constant and gain constant, respectively

$T_{B5}, T_{B6}, T_{B7}$: Exciter time constant and gain constant, respectively

$T_{AB}, K_{AB}$: Stabiliser circuit time constant and gain constant, respectively

$T_{EB}, K_{EB}$: ORCID

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RES Microgrid parameters

\[
D_{FS} = \frac{\partial P_L}{\partial f} = \frac{P_L}{P_R \times f} = 0.0013 \text{pu kW} / \text{Hz}
\]

\[
K_{FS} = 1/D_{FS} = 88.46 \text{Hz/puKW}. \quad T_{FS} = 15s
\]

\[
D_{VS} = \frac{\partial Q_L}{\partial V} = \frac{Q_L}{Q_R \times V} = \frac{P_L}{Q_R \times V}
\]

\[
= 0.57 \text{pu kVAR/puV} \quad K_{VS} = 1/D_{VS} = 1.77 \text{pu kVAR/puV}
\]

\[
T_{VS} = 0.002513 \text{sec}
\]

IRES microgrid parameters

\[
D_{FS} = \frac{\partial P_L}{\partial f} = \frac{P_L}{P_R \times f} = 0.0133 \text{pu kW} / \text{Hz}.
\]

\[
K_{FS} = 1/D_{FS} = 75 \text{Hz/puKW}.
\]

\[
T_{FS} = 15s.
\]

\[
D_{VS} = \frac{\partial Q_L}{\partial V} = \frac{Q_L}{Q_R \times V} = \frac{P_L}{Q_R \times V} = 0.67 \text{pu kVAR/puV}.
\]

\[
K_{VS} = 1/D_{VS} = 1.5 \text{pu kVAR/puV}.
\]

\[
T_{VS} = 0.00212 \text{sec}
\]

Grid

| $P_G$ | $Q_G$ |
|---|---|
| 0.2 pu | 0.09686 pu |

| $K_{IG}$ | $K_{XG}$ | $K_{KG}$ | $K_{AG}$ |
|---|---|---|---|
| -2.874 | 0.2 | 0.2 | -2.681 |

Biogas

| $P_B$ | $Q_B$ |
|---|---|
| 0.2062 pu | 0.0998 pu |

| $X_B$ | $X_B'$ | $T_{B0}$ | $T_B$ |
|---|---|---|---|
| 1 pu | 0.15 pu | 0.0 s | 0.75 s |
| $T_{B1}$ | $T_{B2}$ | $T_{B3}$ | $T_{B4}$ |
| 0.01 s | 0.02 s | 0.15 s | 0.2 s |
| $T_{B5}$ | $T_{B6}$ | $T_{B7}$ | $K_{AB}$ |
| 0.014 s | 0.04 s | 0.036 s | 200 |
| $T_{AB}$ | $K_{EB}$ | $T_{EB}$ | $K_{FB}$ |
| 0.05 s | 1.0 | 2.0 s | 0.5 |
| $T_{FB}$ | $K_{IB}$ | $K_{IB'}$ | $K_{IB}$ |
| 0.1 s | 0.15 | 0.846 | 2.86 |
| $K_{IB}$ | | -3.039 |

WECS

| $P_{WS}$ | $Q_{WS}$ |
|---|---|
| 0.1739 pu | 0.2326 pu |

| $X_{WS}$ | $T_{WS}$ | $K_{WS1}$ | $K_{WS2}$ | $K_{WS3}$ | $K_{WS4}$ |
|---|---|---|---|---|---|
| 0.36 pu | | 2.99 | 2.99 | 0.161 | 0.17 |
| $K_{WS5}$ | $K_{WS6}$ | $T_{WS1}$ | $T_{WS2}$ | $K_{WS7}$ | $K_{WS8}$ |
| -0.17 | -0.17 | | | 2.124 | -2.57 |

Biogas

| $P_B$ | $Q_B$ |
|---|---|
| 0.2062 pu | 0.0998 pu |

| $X_B$ | $X_B'$ | $T_{B0}$ | $T_B$ |
|---|---|---|---|
| 1 pu | 0.15 pu | 0.0 s | 0.75 s |
| $T_{B1}$ | $T_{B2}$ | $T_{B3}$ | $T_{B4}$ |
| 0.01 s | 0.02 s | 0.15 s | 0.2 s |
| $T_{B5}$ | $T_{B6}$ | $T_{B7}$ | $K_{AB}$ |
| 0.014 s | 0.04 s | 0.036 s | 200 |
| $T_{AB}$ | $K_{EB}$ | $T_{EB}$ | $K_{FB}$ |
| 0.05 s | 1.0 | 2.0 s | 0.5 |
| $T_{FB}$ | $K_{IB}$ | $K_{IB'}$ | $K_{IB}$ |
| 0.1 s | 0.15 | 0.846 | 2.86 |
| $K_{IB}$ | | -3.039 |

WECS

| $P_{WS}$ | $Q_{WS}$ |
|---|---|
| 0.1333 pu | 0.1658 pu |

| $X_{WS}$ | $T_{WS}$ | $K_{WS1}$ | $K_{WS2}$ | $K_{WS3}$ | $K_{WS4}$ |
|---|---|---|---|---|---|
| 0.47 pu | | 2.293 | 2.293 | 0.123 | 0.133 |
| $K_{WS5}$ | $K_{WS6}$ | $T_{WS1}$ | $T_{WS2}$ | $K_{WS7}$ | $K_{WS8}$ |
| -0.133 | -0.13 | | | 2.12 | -1.96 |
### PV

| $P_{PVS}$ = 0.1304 pu | $Q_{PVS}$ = 0.1621 pu |
|-----------------------|-----------------------|
| $X_{TPVS}$ = 0.36 pu  | $T_{PV}$ = 0.001 s    |
| $K_{PVSS1}$ = 2.25     | $K_{PVSS2}$ = 2.25    |
| $K_{PVSS}$ = −0.1      | $K_{PVSS}$ = −0.1     |

### Interconnection data

| $R$ = 0.05 pu  | $X = 0.00676$ pu | $P_{RES}$ = 50 kW | $P_{IRES}$ = 40.6 kW |
|----------------|-----------------|------------------|---------------------|
| $P_{LOSS}$ = 9.39 kW | $K_1 = 19.68$ | $K_2 = −19.61$ | $K_3 = 2.364$ |
| $K_4 = 2.364$ | $K_5 = −2.95$ | $K_6 = −19.68$ |