Smart/Micro Grids Research Center
smgrc
Copyright © Smart/Micro Grid Research Center, 2020

ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Energy Reports 6 (2020) 179–186

www.elsevier.com/locate/egyr

The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019),
20–23 September 2019, Okinawa, Japan

Interconnected microgrids frequency response model: An inertia-based approach

S. Rehimi, R. Mirzaei, H. Bevrani*

Smart/Micro Grids Research Center, Department of Electrical and Computer Eng., University of Kurdistan, Iran

Received 3 October 2019; accepted 22 November 2019

Abstract

Preserving the frequency stability of new important blocks in smart grids such as interconnected microgrids, is a serious challenge. Inertia can act as a significant stability/performance index for frequency regulation in the power grids. Renewable energy sources have low inertia and mostly need a special control mechanism to emulate an inertia and inject to the system. In this work, a frequency response model is introduced for AC interconnected microgrids based on the inertia concept. The absence of a suitable model for study on frequency and tie-line power control in the interconnected microgrids, limits research activities in this field. A clear classification has not been done considering the inherent dynamic behavior of all distributed generators types, which may help researchers to introduce more simple strategies to provide better dynamic performance. This paper addresses a new approach for study on inertia-based simple frequency response model for interconnected microgrids. The outcome can be useful for frequency and tie-line power control analysis and synthesis in interconnected microgrids.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Interconnected microgrids; Frequency response model; Frequency control; Tie-line control; Virtual inertia

1. Introduction

Distributed generators (DGs) such as wind turbines (WTs), photovoltaic (PV) and energy storage systems (ESSs) may build a low/medium voltage power grids named microgrids (MGs). Due to environmental concerns, improving performance and reliability of power grids, there is an increasing interest in using of MGs [1]. It is predictable that in the future, interconnected microgrids (IMGs) provide a new application face of smart grids. The IMGs improve reliability, resiliency and flexibility of the future power generation systems [2–6].

One of the important challenges for study on frequency control in AC IMGs, is the absence of suitable dynamic frequency response model (FRM). As mentioned in [7], modeling can be done for variety of purposes. Thus, using a comprehensive model for a special purpose, is not a reasonable choice, and it is better to suggest a model for coinciding on a specific study purpose.

---

* Corresponding author.
E-mail address: bevrani@uok.ac.ir (H. Bevrani).

https://doi.org/10.1016/j.egyr.2019.11.060

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

The present paper provides a simplified FRM for AC IMGs for study on frequency and tie-line power control, which in power grids is known as load frequency control (LFC). In this paper, a new classification is presented for all types of DGs based on their inertia characteristic. According to this classification, an equivalent transfer function is obtained for each type. Then, a simplified FRM is derived for a single connected microgrid. Finally, considering tie-line power, the obtained FRM is modified for AC IMGs and a new equivalent model is presented which is suitable for frequency and tie-line power control analysis and synthesis studies.

The rest of this paper is adjusted as follows: Section 2 presents three categories for DGs such as WT, PV, ESS and diesel generator. In Section 3, a FRM is obtained for a single microgrid. In Section 4, the mentioned FRM is generalized for AC IMGs. Simulation of the proposed model is analyzed in Section 5. Finally, the conclusions are given in Section 6.

2. Three DGs categories

Dynamic analysis and providing a dynamic model for power grid is a hard task due to several reasons such as high number of components to be taken into account, non-linear behavior and complex coupling between components and dynamics [8]. For these reasons, after determining the purpose of the study, separating effective and ineffective dynamics for a special purpose, provides a good solution to obtain a suitable dynamic model for the problem at hand [7]. In this work, an FRM for AC IMGs is presented using the inertia concept. When an event occurred in a power grid, the grid frequency changes according to the system inertia and power imbalance as described by the following well-known swing equation:

$$\Delta P_m(t) - \Delta P_L(t) = 2H\frac{d\Delta f(t)}{dt} + D\Delta f(t) \tag{1}$$

where, Δf is the frequency deviation, $\Delta \mathrm{P_m}$ is the mechanical power change, $\Delta \mathrm{P_L}$ is the load change, H is the inertia constant, and D is the load damping coefficient.

On the other hand in the power grids, inertia, power imbalance and frequency deviation are interdependent. Power imbalance is affected by consumption and production parts. Thus, it is not an inherent characteristic for the power grid components. But inertia is an inherent property for power grids in frequency response point of view [9]. Therefore, inertia can be selected as a significant categorizing index. In distribution generators sources, two indices are selected as effective dynamics on frequency response: inertia and the overall (high) time constant of DGs. The overall time constant introduces a time interval that each DG requires for producing energy according to its natural properties. Inertia introduces the system trends to maintain its current state. In this work, inertia is selected as an index to categorize DGs. Therefore, DGs can be sorted by 3 different categories:

i. **Mechanical type** which presents synchronous generators (SGs) type such as diesel generators, gas turbine and direct connected WTs.
ii. **Chemical type** which presents storage systems such as batteries.
iii. **Electrical type** which presents inverter-based DGs such as PV and indirect connected (power electronic interfaced) WTs.

In this work, it is assumed each MG consists of a direct connected WT, a diesel generator, a solar panel, indirect connected WT and an ESS as shown in Fig. 1.

2.1. Mechanical type

In the mechanical DGs, a mechanical process such as a rotating heavy mass leads to produce electricity. Therefore, inertia and time constant are depended on a mechanical process. It is clear that a heavy mass takes several seconds to rotate at a fixed speed. Although, according to Newton's first law, this rotating mass tends to keep its current state. Thus, when an event occurred, it takes a few seconds to be affected. This property is a good index for the system robustness against disturbances. Because in this condition, a disturbance cannot affect rotational speed immediately. In fact, rotational speed has a direct effect on frequency as follows:

$$\omega = 2\pi f \tag{2}$$

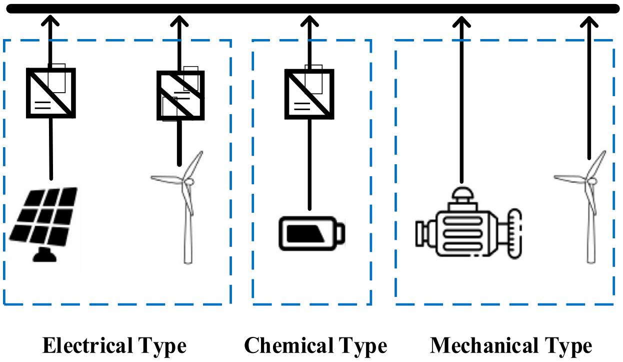

Fig. 1. DGs classification in an MG based on inertia concept.

Thus, in this type, inertia acts as a natural controller for the system against frequency deviation and for large power system with the number of SG-based DGs, high inertia can be considered as a frequency stability index for the whole system. Although, interval time which is needed for produced electricity can be presented as a time delay, (T_m).

2.2. Chemical type

The chemical DGs produce electricity based on a chemical process, e.g., in a lithium-ion battery, an interval time is needed for charging or discharging the battery capacity. In this process, lithium ions move in the electrolyte liquid and this process causes charging/discharging of the battery. But its inertia property is not visible as inertia of mechanical type. Because it is not a physical process and the nature of this inertia is different. Thus, it cannot affect frequency deviation directly and a control mechanism is needed. Therefore, this type of inertia is presented as a virtual inertia. Here, if an event occurred, according to the swing equation, with the change of ΔP and Δf, a feedback will be sent to virtual inertia control loop and the saved energy is injected to the system as extra power to maintain frequency in nominal value, or the extra power of the system is absorbed by charging the battery. In other hand, virtual inertia is able to control frequency deviation virtually. Here, time delay which is needed to generate energy, is presented as T_c.

2.3. Electrical type

In the electrical DGs, electricity is produced based on an electrical process, e.g., moving electrons by solar radiation on solar panels or produced electricity from indirect WTs which they are connected to the grid via power electronics converters. However, in this electrical based process, an interval time is needed to generate energy, and the produced electricity is stored in dc-link or super capacitor for solar panels and in ESSs for indirect WTs. Therefore, inertia could be presented similar to the previous part. Inertia in this type is lower than the other types. Here. T_e introduces the overall time constant for the DGs, and a special inertia constant is suggested for each type.

Assume, H_M, H_C and H_E represent mechanical type inertia, chemical type inertia and electrical type inertia, respectively. H_M is a constant value, because nature of this type is constant, but H_C and H_E are variable between a maximum and a minimum value as follows:

$$0 \leq H_C \leq H_{C\,max} \tag{3}$$

$$0 \leq H_E \leq H_{E\,max} \tag{4}$$

For more simplification and considering the similar behaviors of H_C and H_E, it is possible to assume

$$H_C + H_E = H_{v\,max}. \tag{5}$$

Then, (3) and (4) can be rewritten as

$$0 \leq H_v \leq H_{v\,max}. \tag{6}$$

Based on (6), when chemical and electrical types cannot inject/absorb power according to their variable nature, inertia cannot be added virtually to the system; e.g., when ESSs or super capacitors need their power for supplying the load and are not able to work on virtual inertia mode, in this condition, $H_v = 0$. Amount of virtual inertia can be estimated by several methods, such as meta heuristic algorithms. In this work, an acceptable range of 2 s–7 s is presented for H_C and H_E according to the previous works [10–13]. Based on this analysis, this equivalent inertia can be helpful to use in the fast dynamic control loops.

3. Simplified FRM for a single microgrid

In this section, a simplified FRM is presented for a single MG based on the given explanation in Section 2. An MG consists of DGs, power electronics devices and local loads. For study on frequency response, power electronic devices could be ignored because of their fast dynamics. Load change is presented as a step function. Thus, DGs are the most important part of this modeling. Each DG could be presented by two properties: a time constant that introduces the overall interval time needed for generation energy, and an inertia constant that introduces ability of DGs to play a key role in frequency stability as a natural behavior. Therefore, in an MG for frequency response modeling, two constants are needed which are introduced by the generation part. A simplified block diagram for FRM is presented in Fig. 2.

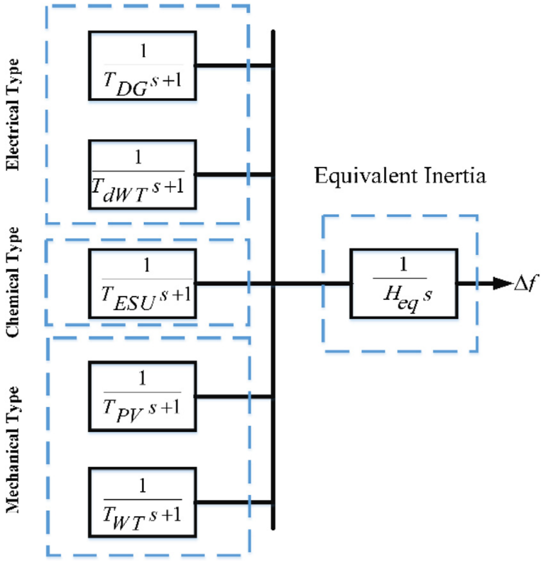

Fig. 2. A simplified block diagram for FRM of a single MG.

Here, T_{DG}, T_{dWT}, T_{PV}, T_{WT} and T_{ESU} present time consents of diesel generator, direct WT, PV, indirect WT and ESS, respectively. Inertia of the whole system can be presented as an equivalent constant (H_{eq}). Here, H_{eq} is assumed as the inertia of the whole system which represents the inertia of all three types of DGs, and

$$H_{eq} = H_v + H_M. \tag{7}$$

4. AC interconnected microgrids FRM

Consider two AC microgrids that are connected as shown in Fig. 3. Each MG can be modeled as presented in Section 3. In this system, an important property is added to the whole structure named tie-line power. In an interconnected two AC MGs, there is a line between MGs for power exchanging. Frequency deviations can be affected when tie-line power is exchanged. Thus tie-line power must be introduced as an effective dynamic on the FRM. Since the IMGs are closed to each other, transmission line between two MGs is not very long, and both resistance and inductance parts of the line must be considered. A time constant using resistance and inductance parameters can be presented as:

$$T_{tie} = \frac{L_{tie}}{R_{tie}} \tag{8}$$

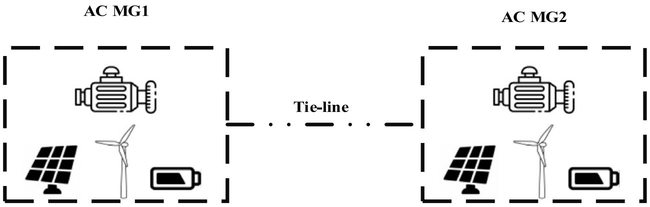

Fig. 3. Two AC IMGs.

where,

$$X_L = R_{tie} + jL_{tie} \tag{9}$$

R_{tie} and L_{tie} are the real and imaginary parts of tie-line impedance, respectively.

Here, L_{tie} and R_{tie} represent the inductance and resistance of the tie-line. Based on this analysis, tie-line power block diagram between IMGs is modeled as shown in Fig. 4. Finally, a completed FRM can be presented as shown in Fig. 5.

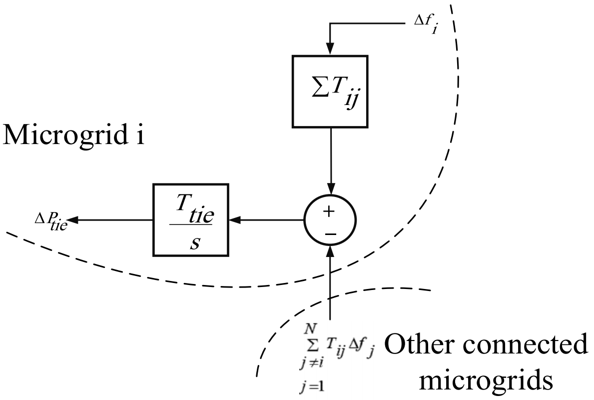

Fig. 4. Tie-line power block diagram between AC IMGs.

5. Simulation results

For validation of the proposed FRM, a single AC MG and two AC IMGs are simulated in MATLAB/Simulink environment. Each MG consists of five DGs. Here, each DG is introduced as a first order transfer function and an overall time constant is presented for each DG to keep its relevant nature frequency dynamic behavior. Fig. 6 shows the test system used here. According to the given analysis in Section 4, the proposed model is simulated in MATLAB/Simulink for a single MG and its behavior is compared with a real AC MG. Fig. 7(a) shows frequency deviation of the test system and Fig. 7(b) shows frequency deviation of the proposed FRM. It is clear that the dynamic behaviors of both models are similar.

Considering tie-line power, the proposed model is applied to two AC IMGs and the results show that dynamic behavior of both AC interconnected models are similar. Fig. 8(a) shows frequency deviation of two AC interconnected test MGs and Fig. 8(b) shows frequency deviation of the proposed FRM.

The tie-line power deviation for two AC IMGs using the proposed FRM, is shown in Fig. 9.

6. Conclusion

In near future, IMGs will be added to smart grids as new autonomous interconnected power grids. However, integrating more renewable energy sources into power grids reduces the number of conventional generation units

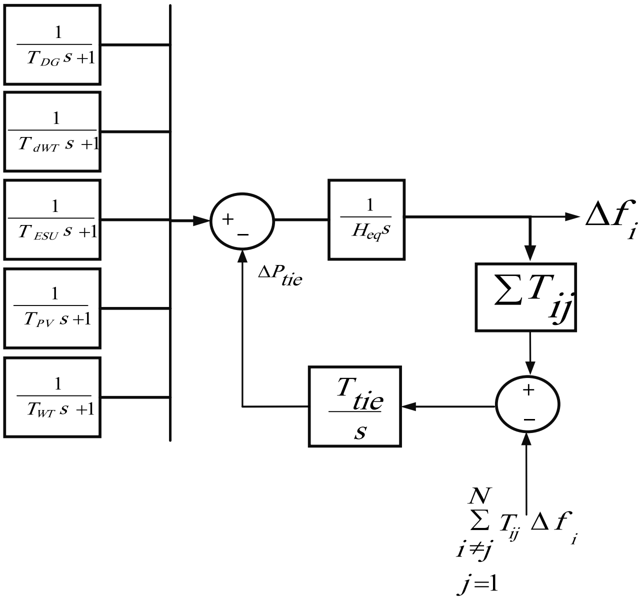

Fig. 5. The overall FRM for AC IMGs.

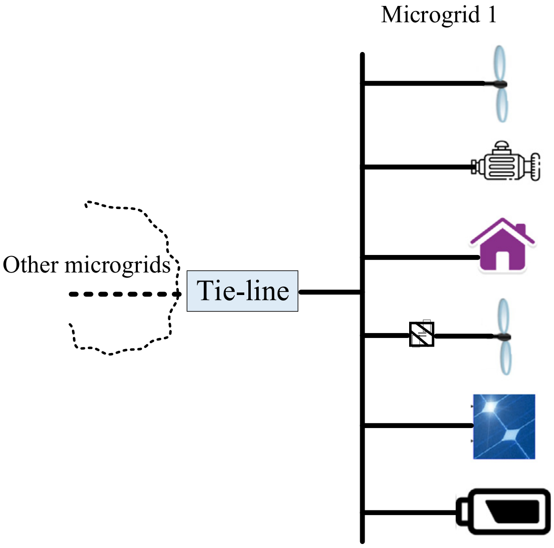

Fig. 6. Test system.

that provide primary frequency control and inertia response. In this paper, a simple FRM for AC IMGs based on inertia concept, is introduced to provide a suitable model for studding on frequency and tie-line power control. This paper addressed several inertia concepts, MG and simplified frequency modeling for single and IMGs. Finally, following a new classification for DGs based on inertia concept, a simple FRM for AC IMGs is presented. The proposed model is validated in MATLAB/Simulink environment and results are compared with two real AC IMGs.

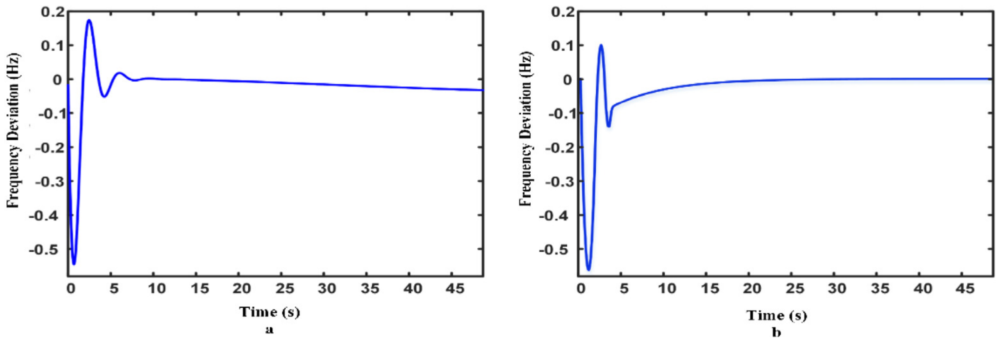

Fig. 7. Frequency response for a single MG; (a) Real test system model (b) Proposed FRM.

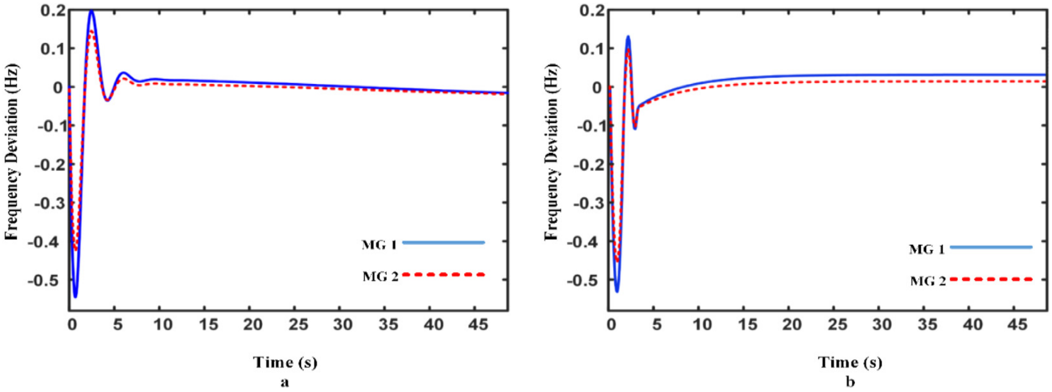

Fig. 8. Frequency response for two AC interconnected MGs; (a) Real test system model (b) Proposed FRM.

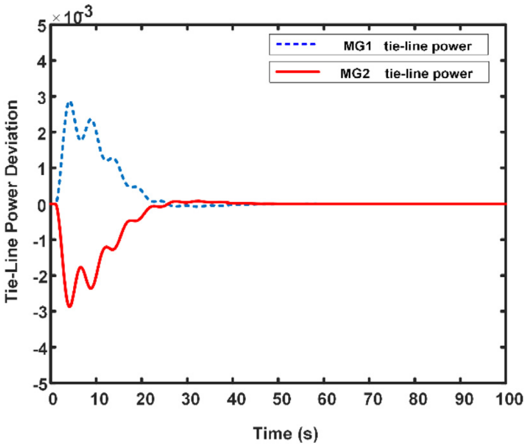

Fig. 9. Tie-line power deviation for two AC interconnected microgrids.

References

[1] Fini MH, Golshan MEH. Determining optimal virtual inertia and frequency control parameters to preserve the frequency stability in islanded microgrids with high penetration of renewables. Electr Power Syst Res 2018;154:13–22.

[2] Lasseter RH. Smart distribution: Coupled microgrids. Proc IEEE 2011;99(6):1074–82.

[3] Schneider KP, et al. Improving primary frequency response to support networked microgrid operations. IEEE Trans Power Syst 2018;34(1):659–67.

[4] Oñate M, Posada J, López J, Quintero J, Aredes M. Control of a back-to-back converter as a power transfer system using synchronverter approach. IET Gener Transm Distrib 2018;12(9):1998–2005.

[5] Shahidehpour M, Li Z, Bahramirad S, Li Z, Tian W. Networked microgrids: Exploring the possibilities of the IIT-Bronzeville grid. IEEE Power Energy Mag 2017;15(4):63–71.

[6] Zhang Y, Xie L, Ding Q. Interactive control of coupled microgrids for guaranteed system-wide small signal stability. IEEE Trans Smart Grid 2015;7(2):1088–96.

[7] Bevrani H, François B, Ise T. Microgrid Dynamics and Control. John Wiley & Sons; 2017.

[8] M.-R. JL, Casado-Machado Francisco, Marano-Marcolini Alejandro. Simplified models for frquency studies in electrical power systems, in: IEEE Power Tech. Milan, 2019.

[9] Bevrani H. Robust Power System Frequency Control. second ed. Springer; 2014.

[10] Dreidy M, Mokhlis H, Mekhilef S. Inertia response and frequency control techniques for renewable energy sources: A review. Renew Sustain Energy Rev 2017;69:144–55.

[11] Waffenschmidt E, Hui RS. Virtual inertia with PV inverters using DC-link capacitors. In: 2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), 2016. IEEE; 2016, p. 1–10.

[12] Torres M, Lopes LA. Virtual synchronous generator: A control strategy to improve dynamic frequency control in autonomous power systems. Energy Power Eng 2013;5(02):32.

[13] Kheshti M, Ding L, Nayeripour M, Wang X, Terzija V. Active power support of wind turbines for grid frequency events using a reliable power reference scheme. Renew Energy 2019;139:1241–54.