A Control Strategy for Flywheel Energy Storage System for Frequency Stability Improvement in Islanded Microgrid

A. A. Khodadoost Arani*, B. Zaker* and G. B. Gharehpetian*(C.A.)

Abstract: The Micro-Grid (MG) stability is a significant issue that must be maintained in all operational modes. Usually, two control strategies can be applied to MG; V/f control and PQ control strategies. MGs with V/f control strategy should have some Distributed Generators (DGs) which have fast responses versus load changes. The Flywheel Energy Storage System (FESS) has this characteristic. The FESS, which converts the mechanical energy to electrical form, can generate electrical power or absorb the additional power in power systems or MGs. In this paper, the FESS structure modeled in detail and two control strategies (V/f and PQ control) are applied for this application. In addition, in order to improve the MG frequency and voltage stability, two complementary controllers are proposed for the V/f control strategy; conventional PI and Fuzzy Controllers. A typical low voltage network, including FESS is simulated for four distinct scenarios in the MATLAB/ Simulink environment. It is shown that fuzzy controller has better performance than conventional PI controller in islanded microgrid.

Keywords: Flywheel Energy Storage System (FESS), Fuzzy Controller, Microgrid (MG), Voltage and Frequency Stability, Stored Energy.

1. Introduction

The Microgrid (MG) is a low voltage network that usually consists of loads, one or more Distributed Generators (DGs) and energy storage systems. Photovoltaic Cell (PV), Fuel Cell (FC), Microturbine (MT), Wind Turbine (WT) and small synchronous generator are some of these DGs which can be used in MGs. Besides these, Battery Energy Storage System (BESS), Flywheel Energy Storage System (FESS) and super capacitor are some examples of storage systems that may be used in a MG [1-5]. Fig. 1 shows a typical MG.

A MG can operate in two operational modes; grid connected and isolated modes. When the MG operates in grid connected mode, the main grid supports MG stability and dictates the frequency and voltage in all over the MG which operates in PQ control mode. While when it is disconnected from the main grid, it operates in V/f control mode [6-8].

FC, MT and other kinds of DGs with slow dynamics are usually controlled by the PQ control strategy in both MG operation modes. However, DGs with the capability of the V/f control strategy, should have a fast response to load changes. The FESS, BESS and diesel generators almost have this characteristic and can swiftly change their generation or absorption [9-12].

The BESS has been used in [9], to enhance the MG stability. In this case, a strategy that acts based on frequency deviations has been defined. Actually, the BESS has a basic role alongside other DGs with the PQ control strategy. Although batteries have some advantages like relia-

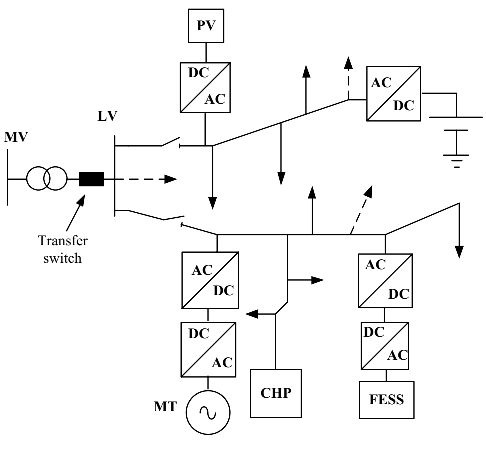

Fig. 1. Architecture of typical MG

Iranian Journal of Electrical & Electronic Engineering, 2017.
Paper received 12 October 2016 and accepted 8 March 2017.
* The authors are with the Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran.
E-mails: a.a.khodadoost@aut.ac.ir, zaker.behrooz@aut.ac.ir and grptian@aut.ac.ir
Corresponding Author: G. B. Gharehpetian.

bility, high rating (series and parallel implementation), cost-effective and high energy density, they have some drawbacks such as low power density, higher maintenance requirements and environmental issues and concerns. Although the Battery can discharge rapidly like FESS, it cannot charge rapidly [13].

On the other hand, in comparison to BESS, the FESS is environmentally friendly, requires no remarkable maintenance and has high power density. Due to these advantages, the FESS can be used for different applications in power systems and MGs such as power quality improvement [15, 16] and stability enhancement [17].

In [18], the FESS modeling has been introduced and used for a MG including a diesel generator and critical loads. In [19, 20], the authors have tried to mitigate frequency oscillations by using FESS in a power system including wind power plants. That scheme required a smart communication network among sources. Indeed, the FESS had a complementary role in this case. The application of the FESS in [21-22], causes more penetration of renewable energies, and indeed the FESS has increased reliability in MG by improving its stability. The Authors show that application of the FESS in distribution systems has improved voltage and frequency control [23].

In some works such as [36-37], a fuzzy controller for the FESS has been used to regulate the power in presence of wind power generation units. The wind generation units have many fluctuations. The application of fuzzy controller has improved the power generation curve of the FESS with these units.

In [23], a survey of FESS applications and different control strategies has been presented. A FESS with V/f control and PQ control strategies has been used in [24] and the results on the MG stability have been presented for these control strategies. However, the model applied for FESS, is an ideal DC voltage source connected to an inverter. Therefore, the dynamics of FESS has been neglected. Also, some limitations of state-of-charge and speed have been disregarded. Actually, the authors have neglected the primary dynamics of the FESS and consequently the dynamic behavior of the MG has been ignored in the studied cases. Since the FESS is not a long-term energy storage device and has a low capacity of energy, the results of the detailed model are different from this model. This is important for maintenance studies, as well. Due to the limited energy capacity of the FESS, a charge and discharge rule should be determined for it.

In this paper, a comprehensive and detailed model of the FESS is initially introduced. Then, different control strategies (PQ and V/f) are applied to this model. In addition, a complementary scheme is proposed and added to FESS with the V/f control strategy. To compare the effect of applied strategies on the MG frequency and voltage stability, the FESS with three control strategies, is studied in the low voltage network of CIGRE [25]. The simulation results are presented in the fourth section of the paper. In each simulation scenarios, the voltage and frequency have been analyzed. In addition, the power and energy of the FESS, as an important factor for this energy storage system, have been discussed. An appropriate long term control scheme on electrical power of the FESS and other DGs should be applied to maintain the stability of MG. Finally, a conclusion of the paper is presented.

2. FESS Structure

Briefly, a massive disk, which is connected to an electrical machine shaft and its velocity and power flow (to or from MG) can be controlled, is called FESS. The electrical model of a FESS consists of an electrical machine, a back to back converter and its control system and a massive disk (flywheel). Fig .2 shows a general scheme of FESS. The stored energy in the FESS can be computed as follows:

$$E_{FESS} = \frac{1}{2} J_f \omega^2 \tag{1}$$

where, Jf (kg.m²) and ω (rad/s) are the flywheel inertia moment and speed, respectively. In low speed FESS, the velocity approximately reaches up to 10000 rpm and thus for storing more energy, based on (1), the inertia of the disk should be increased [13, 22, 26].In this case the inertia has been increased, therefore, a low speed FESS has been used.

Based on (1), the State-of Charge (SoC) of the FESS can be defined as follows:

$$SoC_{FESS}(\%) = \frac{E(t)}{E_0} = \frac{1}{E_0}\frac{1}{2} J_f \omega^2(t) \tag{2}$$

where E0 is the initial stored energy in the FESS and ω can be achieved in each time which is sensed by a speed sensor, consequently the SoC of the FESS can be computed comfortably.

In this study, an Induction Machine (IM) is used in the FESS scheme. For modeling of the inertia of the disk, an additional inertia has been set for IM. Also, the FESS has a back to back converter, including two converters and a DC link. One of these converters (machine-side converter) controls IM, and adjusts its speed while the other converter connects the FESS to the MG. According to the different conditions such as MG operation mode, state-of-storage charge etc., the direction of the power flow in the FESS is determined and it is implemented by controlling two converters.

3. Modeling of FESS

3. 1. Machine-side converter control

To control the machine-side converter, the direct field-oriented control (DFOC) is used. The detailed procedure of this control method has been stated in and shown in Fig 3. For an IM with p pairs of pole, the operation equation in the stator reference frame, as space vectors, can be written as follows [27-29]:

$$\overline{v}_s = R_s \overline{i}_s + \frac{d\overline{\varphi}_s}{dt} \tag{3}$$

$$0 = R_r \overline{i}_r + \frac{d\overline{\varphi}_r}{dt} - j\omega_m \overline{\varphi}_r \tag{4}$$

$$\overline{\varphi}_s = L_s \overline{i}_s + M \overline{i}_r \tag{5}$$

$$\overline{\varphi}_r = L_r \overline{i}_r + M \overline{i}_s \tag{6}$$

$$T = p\frac{M}{\sigma L_s L_r}(j\overline{\varphi}_r . \overline{\varphi}_s) \tag{7}$$

where, R_r and R_s are the rotor and stator resistance, respectively, and Lr and Ls are the rotor and stator inductance, respectively. M is the no-load inductance of the IM and φ, i, and v indicate the flux, current and voltage and σ is defined as follows:

$$\sigma = 1 - \frac{M^2}{L_s L_r} \tag{8}$$

In the rotor reference frame, considering the d-q frame and developing the above equations, the torque and flux can be stated as follows:

$$\frac{d\varphi_{rd}}{dt} + \frac{1}{\tau_r}\varphi_{rd} = \frac{M}{\tau_r} i_{sd} \tag{9}$$

$$T = \frac{3}{2} p \frac{M}{L_r} \varphi_{rd} i_{sq} \tag{10}$$

Equations (9) and (10) that are the basic equations in the FOC method show that in the rotor flux reference frame, the rotor flux and torque can be obtained. An important outcome is achieved showing that the decoupled control of the rotor flux and torque by using d and q components of the stator current is practical. However, this method requires knowledge of rotor flux position. The block diagram of the Direct Field Oriented Control (DFOC) is shown in Fig. 3.

In this method, the reference of the rotor flux and machine torque is estimated by measuring the rotor speed and stator current. Then, the reference of the flux and torque, obtained at a higher control level, is compared with the estimated values. Thereafter, to set the flux and torque of the machine in a predefined value, a reference voltage is generated and finally this voltage is delivered in machine terminals by using a Space Vector Pulse Width Modulation (SVPWM) technique [15].

3. 2. Grid-side convertor control

The grid-side converter is controlled by a vector-oriented control (VOC) method. A Phase Locked Loop (PLL) is used in this control method for grid synchronization. This method has been stated in detail in [29] and its structure is shown in Fig. 4.

An important issue is the determination of reference values of currents in this method, which is shown in Fig.

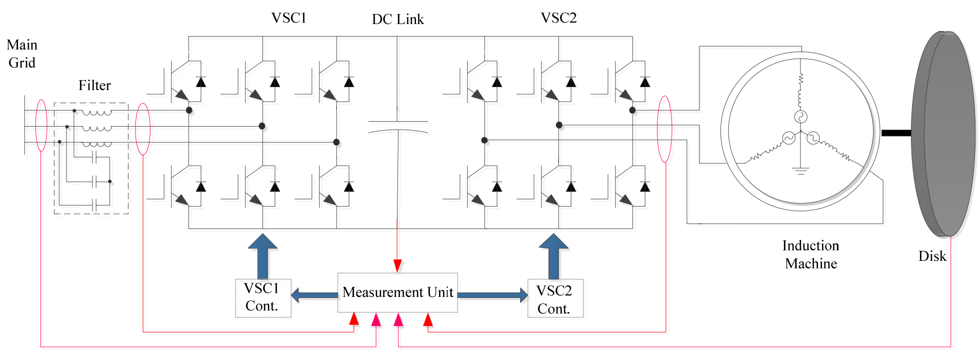

Fig. 2. General scheme of FESS

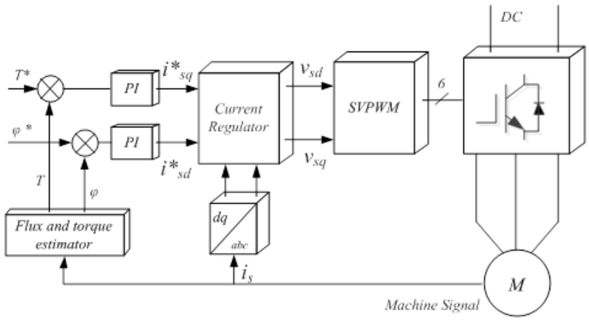

Fig. 3. Block diagram of FOC [38].

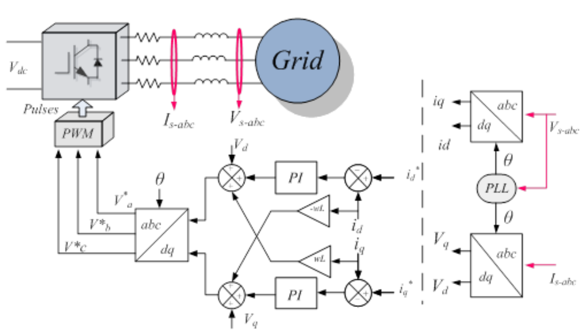

Fig. 4. Control of grid-side convertor [38].

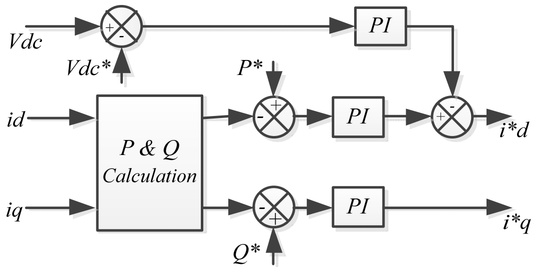

Fig. 5. Reference currents determination in grid-side converter controller.

5.These references, can be determined for maintaining DC voltage of the DC link in nominal value or supplying a distinct value of active and reactive power or both. The power calculation unit operates as follows:

$$P = v_{sd} i_d + v_{sq} i_q \tag{11}$$

$$Q = v_{sd} i_q - v_{sq} i_d \tag{12}$$

3. 3. Control of FESS

In this section, the proposed control structure is described. Two control strategies can be applied on FESS: V/f and PQ control strategies. In the V/f control strategy, the FESS unit has been used as a reference voltage and frequency unit in MG. Therefore, the grid-side converter must control the frequency and voltage. The reference of the voltage and frequency are achieved based on droop equations as follows [30-35]:

$$f = f^* - mP \tag{13}$$

$$V = V^* - nQ \tag{14}$$

where, f* and V* are the no-load frequency and voltage respectively, and m and n are droop coefficients. Also, complementary control includes two PI controllers the input of which is the feedback of the frequency and voltage, which are added to the no-load frequency and voltage. In addition a fuzzy controller can be used for this purpose, as has been shown in Fig. 6.

The fuzzy controller which has been designed in this

Table 1. Fuzzy control rules for computation

		Frequency						
		PB	**PM**	**PS**	**ZE**	**NS**	**NM**	**NB**
df/dt	**N**	NM	NS	ZE	ZE	PS	PM	PB
	Z	NB	NM	NS	ZE	PS	PM	PB
	P	NB	MB	NS	ZE	ZE	PS	PM

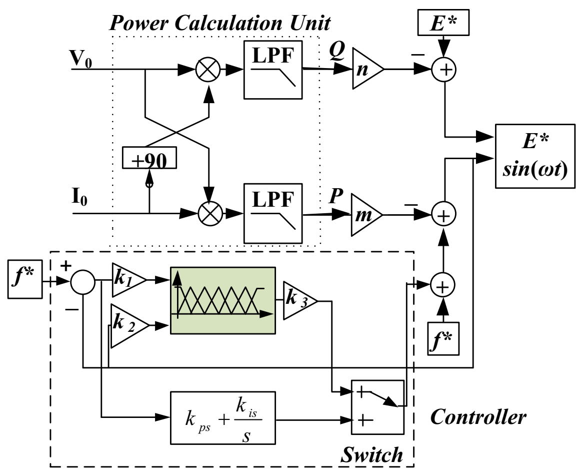

Fig. 6. V/f control strategy with complementary control.

paper has two input and one output. All inputs and output have been normalized in range of [-1, 1]. Input 1 represents the normalized value of frequency changes in MG which has seven Membership Functions (MFs). The MFs have been selected as triangular shape and their overlap firstly has been selected 50% and then has changed by try and error by expert person.

For input 2, three MFs have been selected and the output has seven MFs. Fig. 7 show the input and output MFs. Table 1 lists the rules of fuzzy inference system.

Application of the droop and complementary controls retrieve the frequency to its nominal value. The droop method leads to stable operation of the V/f controlled inverter. Due to a sudden change of active power in the MG, the V/f controlled DG (that is, the FESS) should respond to it. Based on the droop method by increasing the generation of the FESS, the frequency is dropped. Indeed the relation between the changes of frequency with respect to active power changes are always negative, as follows:

$$\frac{\partial f}{\partial P} < 0 \tag{15}$$

This ensures the stability of the system. On other hand, the complementary control helps to set the frequency in an acceptable range by changing no-load frequency and leads to a stable operation mode. As can be seen, an increment in P leads to a frequency drop. As a result, the input of the PI controller is increased which causes no-load frequency change.

To ensure that the voltage of the DC link has no fluctuation, the voltage control of the DC link is essential. The machine-side converter controls the power flow between DC link and machine and tries to keep it constant by changing the machine speed. This strategy is shown in Fig. 8. If FESS is adjusted by the PQ control, the grid-side converter works as DC link voltage stabilizer and the machine-side converter sets the disk speed. The reference speed is determined using Pref. To calculate the speed reference (ωref), firstly, the energy reference of the FESS is computed by using Pref and then, ωref can be written, as follows:

$$E_{ref} = E_0^{t_1} + \int_{t_1}^{t} P_{ref}\, dt \tag{16}$$

$$\omega_{ref} = \sqrt{\frac{2E_{ref}}{J_{fw}}} \tag{17}$$

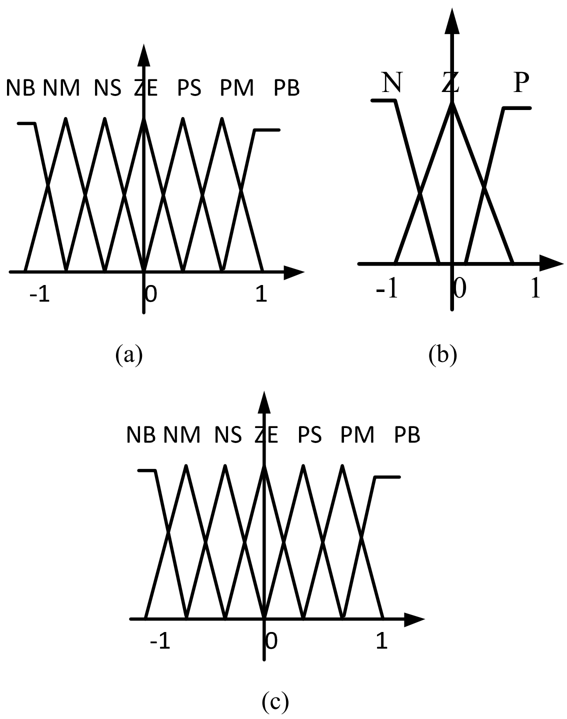

Fig. 7. Membership function of ; a: Input1 (frequency of MG), b: Input2 (changes of frequency) and c: Output.

4. Simulation Results

In the simulated MG, a PV and FC are associated by the PQ control strategy based on dynamic modeling applied in [9]. The nominal ratings of PV and FC are 1.5 kVA and 2 kVA respectively. Three scenarios are studied in the simulations. The first scenario has a FESS with PQ control. The second one includes the FESS with V/f control strategy and the third scenario consists of a FESS with V/f control strategy and complementary control scheme. In all of the scenarios, the MG is connected to the main

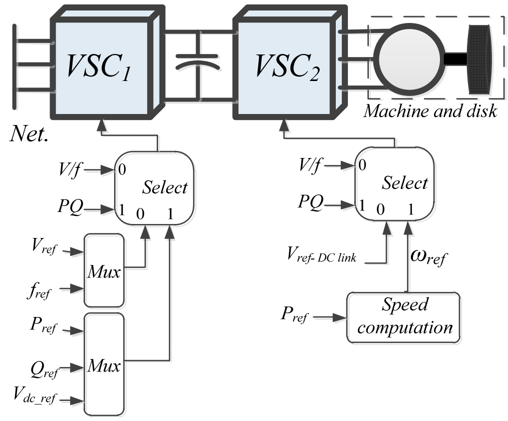

Fig. 8. The overall control structure of FESS.

Table 2. Parameters of FEES.

Parameter	Value	Parameter	value
Nominal Voltage	400 V	Nominal DC voltage Bus	680 V
Nominal Speed	1470 rpm	S nominal	9 kVA
P (pair of poles)	2	Friction	0.0022N.m.s
R_s	0.19 Ω	M	34.3mH
$R_r^{'}$	0.12 Ω	J	3 kg.m^2
L_s	1.952 mH	$L_r^{'}$	1.952 mH

Table 3. Control parameters of the system

Parameter	Value	Parameter	value
DC Regulator k_i	120	DC Regulator k_p	7
Speed Regulator k_i	135	Speed Regulator k_p	3
m	4%	n	10%
k_{ps}	5	k_{is}	1

grid and at t=6s, islanding occurs.

The specifications of the FESS and control parameters, used in the simulations, are listed in Tables 2 and 3. Also, the single diagram of the simulated MG is shown in Fig. 9 and line and load data are given in appendix A. All of loads are static RL load. Considering the initial speed of the FESS and the inertia value, the initial energy of the FESS, using (2), is 36.973kJ.

4.1. Scenario-1

In this scenario, the FESS has a PQ control strategy. Before islanding, the total load of the MG is 2.5 kW and 1.5 kVAR for which 0.5 kW and 0.5 kVAR of this load is supplied by the main grid. After islanding in t=6s, due to the lack of a DG with V/f control strategy, there is a frequency deviation increment. The MG frequency is shown in Fig. 10.a. Moreover, the voltage of the MG has fluctuations, which are not tolerable for MG equipments and DGs and protection relays may trip DGs. The RMS voltage value of one phase and active power of the FESS are

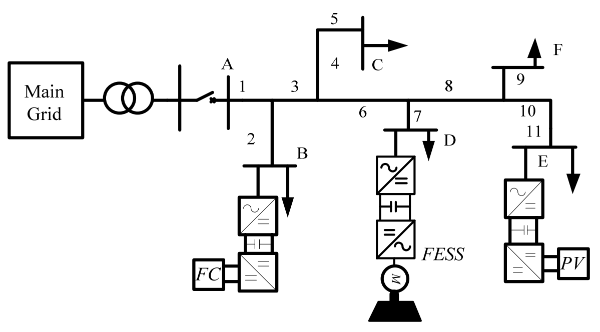

Fig. 9. Architecture of simulated MG.

shown in Figs. 10.b and Fig. 10.c, respectively. As can be seen, the generated power by the FESS has fluctuations and exceeds the nominal power value of FESS which can be prevented . All of the figures show that the PQ controlled operation of the FESS is not suitable in the lack of V/f controlled DGs . Indeed, this situation must not be created which is called as instability of MG. Therefore, a precise control scheme is required for proper operation of the MG.

4. 2. Scenario-2

In this scenario, the V/f control strategy is applied to the FESS. The droop equations are used for the FESS. Based on (12), the frequency is dropped based on generated active power of the FESS. As can be seen, after islanding at t=6s, the frequency drops and does not retrieve to its nominal value. This scheme can act better if the droop coefficient is decreased. Although this scheme helps to improve the voltage and frequency stability of the MG, the frequency reduction is intolerable for loads in MG. Fig. 11.a also shows the frequency of the MG in this scenario. As can obviously be seen, in addition to frequency stability enhancement this scheme, improves the voltage stability in the MG (Fig. 11.b). The active power generated by the FESS, indicates that the system has a stable behavior (Fig. 11.c). From these figures, it can be understood that, so long as the FESS can supply the MG, it operate in stable condition but not the necessarily appropriate condition.

4. 3. Scenario-3

This scenario includes a FESS, which has the V/f control strategy and complementary control for frequency. Similar to the last case, the droop equations are used to control the FESS. In addition to these equations, a complementary control based on frequency deviation and PI controller, is used. The controller parameters are determined by try and error in simulations. Considering the droop characteristic, the frequency decreases but, the complementary controller retrieves it to its nominal value. This is shown in Fig. 12a. This scheme is implemented for the same droop coefficient of the last scenario. This scheme helps to improve stability in the MG .The frequency drop is minimum in the three investigated scenarios. To examine this control strategy, the switching of load in different time steps have been performed. Moreover, Fig. 12.b shows the RMS voltage in this scenario. As can obviously be seen, this scheme effectively enhances the voltage stability in the MG in addition to the frequency. Finally, the FESS active power generation is presented in Fig. 12.c which shows that the FESS has a stable behavior.

For more consideration, the disk speed of the FESS for three scenarios is shown in Fig. 13. Fig. 13.a shows that the FESS is discharged very fast and it cannot support the

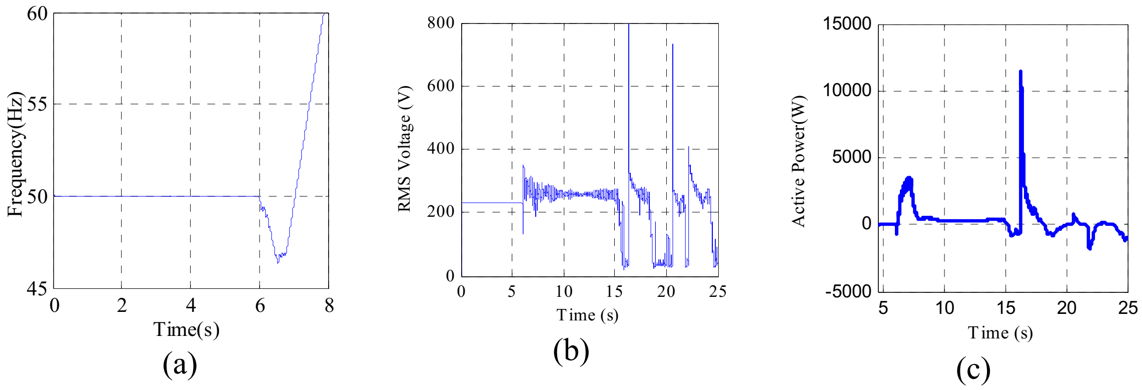

Fig. 10. Electrical Outputs of in scenario-1; a: Frequency of MG, b: Voltage of the FESS and c: Active power of the FESS.

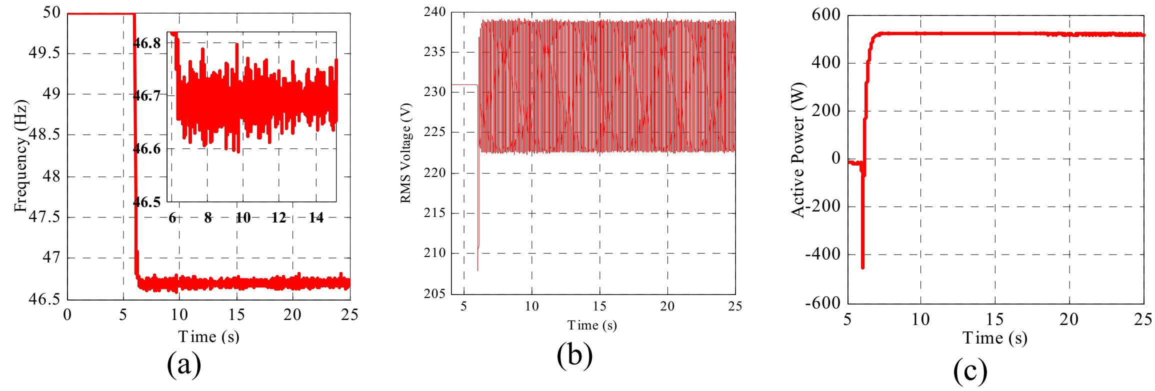

Fig. 11. Electrical Outputs of in scenario-2; a: Frequency of MG, b: Voltage of the FESS and c: Active power of the FESS.

MG stability consequently the instability is created. In Fig. 13.b, it can be seen that the FESS speed decreases slowly. Therefore, the speed of the FESS in two other scenarios verifies the good performance of this storage system. As expected in scenario-3, the speed reduces faster which shows that more power is converted in this scenario. A simple calculation shows that the speed decreases with a rate of 100 rpm in 9s and therefore by considering the lower speed limit (i.e., 500 rpm), the FESS can inject power to MG for 1.5 minutes without any problem. The SoC of the FESS has been shown in Fig.13. c. Considering this figure, it can be understood the stored energy of the FESS, is discharged completely after about several minutes, so a midterm control strategy for the MG and the FESS is necessary.

Figs.14.a and b show the active and reactive power of DGs in MG respectively. These figures show that DGs operate in stable conditions. The total reactive power of DGs and the FESS as expected is almost 1.5 kVAR

.

4. 4. Scenario-4

To test the MG and the FESS operation under load changing, scenario-4 has been simulated. The FESS has been equipped by V/f control and PI controller as compensation controller. This scenario, in addition to islanding, different step changes in active and reactive power of load in bus C and F have been created. Fig. 14.a shows the total active and reactive power of DGs and the FESS which is correspondent to load changing. Different step changing in load are exerted in t= 12s, 18s and 24s. The value of load changing is 200 W and 100 VAR. Fig. 14.b shows the power of the FESS in this scenario.

The frequency of the MG has been shown in Fig. 15.a. The maximum frequency deviation is under 0.6 Hz. The loads is increased in t=12 and 18 and the frequency has been dropped and in t= 24s, the load is decreased and the frequency is increased. However, the MG, in all of situations, the MG operated in stable condition.

In addition, if fuzzy controller is used as complementary controller the frequency response is improved in MG. Fig. 15.b shows the frequency response of MG influenced

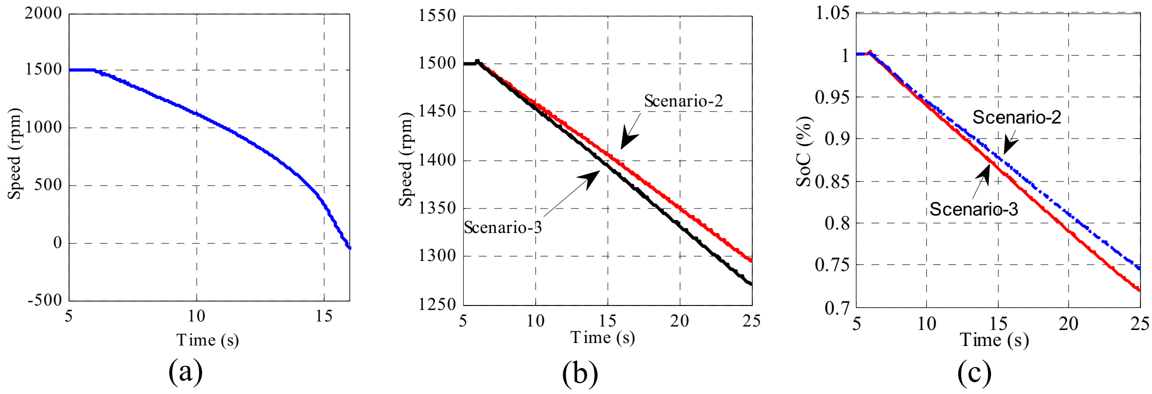

Fig. 12. Speed of FESS; a: Scenario-1, b: Scenario-2, 3 and the SoC of the FESS in scenario 2, 3.

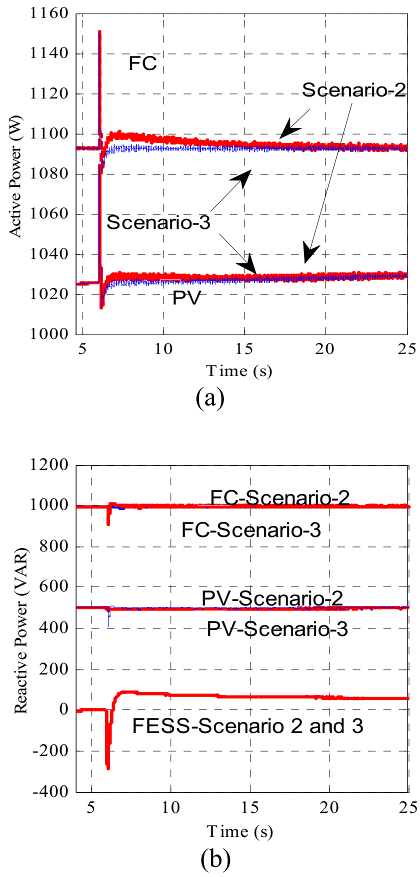

Fig. 13. The Active and reactive power of DGs in scenarios 2, 3.

by the same change in Fig. 14. a which can be seen that the frequency has a good behavior in MG and just islanding could deviate the frequency.

Comparing the result of frequency of the last two cases of control strategy (droop compensating by conventional PI and fuzzy controller) shows that the fuzzy controller has a better response; therefore for mid-term consideration, this type of controller is used.

5. Conclusion

In this paper, a detailed mode1 of the FESS has been

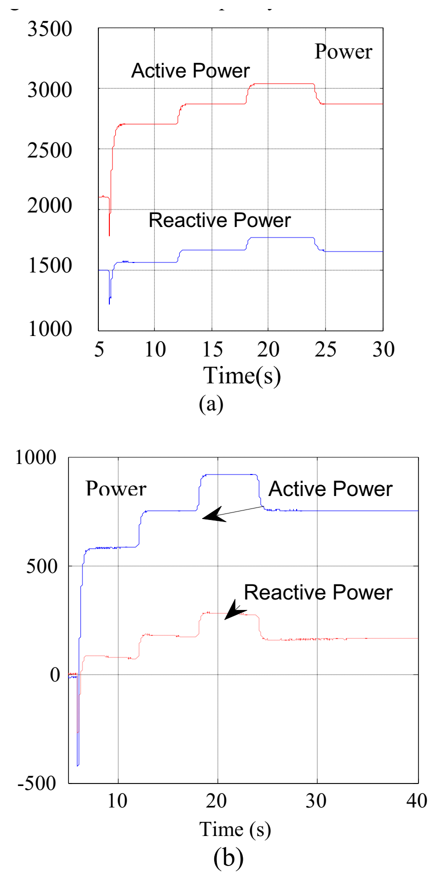

Fig. 14. Scenario-4; a: The total active and reactive power of DGs; b: The total active and reactive power of the FESS

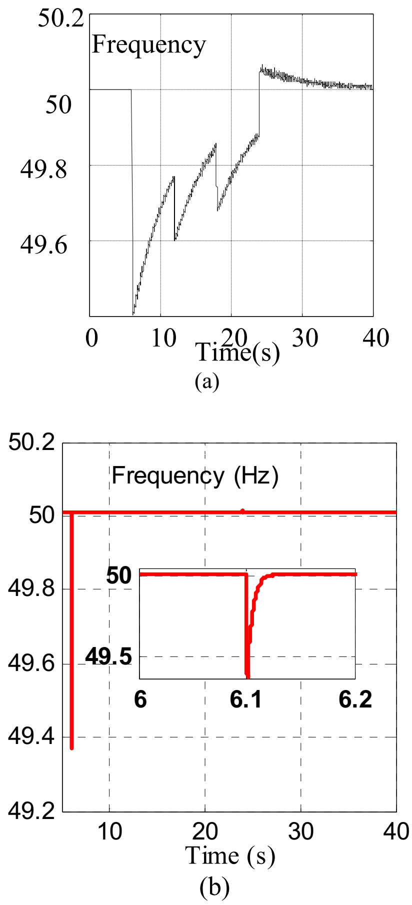

Fig. 15. Scenario-4; The Frequency of MG

presented. The PQ control, V/f control and two complementary controller have been introduced and applied to the FESS. The complementary controllers include a PI controller and fuzzy controller respectively that change the no-load frequency of the FESS in V/f control mode. A generic low voltage network consisting of the FESS and other DGs, has been simulated by MATLAB/Simulink. Three aforementioned control methods have been used for the FESS control in different scenarios and the power and energy of the FESS have been achieved.

In the first scenario, the application of the PQ control strategy causes instability in voltage and frequency of the MG after islanding. In the second scenario, the V/f control method has been applied. In this case, the frequency deviation was more than 3Hz, which was not acceptable. The application of a complementary controllers in addition to the V/f control strategy results in good behavior for the frequency and voltage of the MG. In addition, it could be seen that the fuzzy controller causes a robust and better response for frequency in MG. Moreover, a midterm consideration of MG has been carried out. The future work of this paper is the optimal design of these controllers and its application on a test-bed is to experimentally verify the results.

REFERENCES

[1] Lasseter, Robert H., and Paolo Paigi. "Microgrid: A conceptual solution." In Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual, vol. 6, pp. 4285-4290. IEEE, 2004.

[2] Arani, AA Khodadoost, H. Karami, G. B. Gharehpetian, and M. S. A. Hejazi. "Review of Flywheel Energy Storage Systems structures and applications in power systems and microgrids." Renewable and Sustainable Energy Reviews 69 (2017): 9-18.

[3] Al Sayari, Naji, Rajasekharareddy Chilipi, and Mohamad Barara. "An adaptive control algorithm for grid-interfacing inverters in renewable energy based distributed generation systems." Energy Conversion and Management 111 (2016): 443-452.

[4] Kamarposhti, Mehrdad Ahmadi, Seyed Babak Mozafari, Soodabeh Soleymani, and Seyed Mehdi Hosseini. "Improving the wind penetration level of the power systems connected to doubly fed induction generator wind farms considering voltage stability constraints." Journal of Renewable and Sustainable Energy 7, no. 4 (2015): 043121.

[5] Babić, Iva, Željko Đurišić, and Mileta Žarković. "Analysis of impact of building integrated photovoltaic systems on distribution network losses." Journal of Renewable and Sustainable Energy 7, no. 4 (2015): 043119.

[6] Yao, Wei, Min Chen, José Matas, Josep M. Guerrero, and Zhao-Ming Qian. "Design and analysis of the droop control method for parallel inverters considering the impact of the complex impedance on the power sharing." IEEE Transactions on Industrial Electronics 58, no. 2 (2011): 576-588.

[7] Vasquez, Juan C., Josep M. Guerrero, Alvaro Luna, Pedro Rodríguez, and Remus Teodorescu. "Adaptive droop control applied to voltage-source inverters operating in grid-connected and islanded modes." IEEE Transactions on Industrial Electronics 56, no. 10 (2009): 4088-4096.

[8] Chandorkar, Mukul C., Deepakraj M. Divan, and Rambabu Adapa. "Control of parallel connected inverters in standalone ac supply systems." IEEE Transactions on Industry Applications 29, no. 1 (1993): 136-143.

[9] Kamel, Rashad M., and Bahman Kermanshahi. "Enhancement of micro-grid dynamic performance subsequent to islanding process using storage batteries." Iranian Journal of Science and Technology 34, no. B6 (2010): 605.

[10] Vargas Martínez, Adriana, Luis Ismael Minchala Avila, Youmin Zhang, Luis Eduardo Garza Castañón, and Hamed Badihi. "Hybrid adaptive fault tolerant control algorithms for voltage and frequency regulation of an islanded microgrid." International Transactions on Electrical Energy Systems 25, no. 5 (2015): 827-844.
[11] Wu, Xiong, Xiuli Wang, Jianxue Wang, Chong Qu, Chunyang Liu, and Jie Duan. "Schedule and operate combined system of wind farm and battery energy storage system considering the cycling limits." International Transactions on Electrical Energy Systems 25, no. 11 (2015): 3017-3031.
[12] Zaker, B., A. K. Arani, and G. Gharehpetian. "Investigating battery energy storage system for frequency regulation in islanded microgrid." In 3rd Iranian regional CIRED conf., Tehran, Iran. 2015.
[13] Ribeiro, Paulo F., Brian K. Johnson, Mariesa L. Crow, Aysen Arsoy, and Yilu Liu. "Energy storage systems for advanced power applications." Proceedings of the IEEE 89, no. 12 (2001): 1744-1756.
[14] Luo, Xing, Jihong Wang, Mark Dooner, and Jonathan Clarke. "Overview of current development in electrical energy storage technologies and the application potential in power system operation." Applied Energy 137 (2015): 511-536.
[15] Samineni, Satish, Brian K. Johnson, Herbert L. Hess, and Joseph D. Law. "Modeling and analysis of a flywheel energy storage system for voltage sag correction." IEEE Transactions on Industry Applications 42, no. 1 (2006): 42-52.
[16] Arani, AA Khodadoost, and G. B. Gharehpetian. "Enhancement of microgrid frequency control subsequent to islanding process using flywheel energy storage system." In Smart Grid Conference (SGC), 2014, pp. 1-6. IEEE, 2014.
[17] Wang, Lingfeng, J-Y. Yu, and Y-T. Chen. "Dynamic stability improvement of an integrated offshore wind and marine-current farm using a flywheel energy-storage system." IET Renewable Power Generation 5, no. 5 (2011): 387-396.
[18] Arghandeh, R., Manisa Pipattanasomporn, and Saifur Rahman. "Flywheel energy storage systems for ride-through applications in a facility microgrid." IEEE Transactions on smart grid 3, no. 4 (2012): 1955-1962.
[19] Takahashi, Rion, and Junji Tamura. "Frequency control of isolated power system with wind farm by using flywheel energy storage system." In Electrical Machines, 2008. ICEM 2008. 18th International Conference on, pp. 1-6. IEEE, 2008.
[20] Suvire, Gastón Orlando, Marcelo Gustavo Molina, and Pedro Enrique Mercado. "Improving the integration of wind power generation into AC microgrids using flywheel energy storage." IEEE Transactions on smart grid 3, no. 4 (2012): 1945-1954.
[21] Hamsic, N., A. Schmelter, A. Mohd, E. Ortjohann, E. Schultze, A. Tuckey, and J. Zimmermann. "Increasing renewable energy penetration in isolated grids using a flywheel energy storage system." In Power Engineering, Energy and Electrical Drives, 2007. POWERENG 2007. International Conference on, pp. 195-200. IEEE, 2007.
[22] Díaz-González, Francisco, Melanie Hau, Andreas Sumper, and Oriol Gomis-Bellmunt. "Coordinated operation of wind turbines and flywheel storage for primary frequency control support." International Journal of Electrical Power & Energy Systems 68 (2015): 313-326.
[23] Ahmadi, Roya, Fatemeh Ghardashi, Dawood Kabiri, Abdolreza Sheykholeslami, and Homayun Haeri. "Voltage and frequency control in smart distribution systems in presence of DER using flywheel energy storage system." (2013): 1307-1307.
[24] Wu, Xueguang, Yibin Zhang, Atputharajah Arulampalam, and Nick Jenkins. "Electrical stability of large scale integration of micro generation into low voltage grids." International Journal of Electronics 1, no. 4 (2005): 1-23.
[25] Papathanassiou, Stavros, Nikos Hatziargyriou, and Kai Strunz. "A benchmark low voltage microgrid network." In Proceedings of the CIGRE symposium: power systems with dispersed generation, pp. 1-8. 2005.
[26] Power, Active. "Understanding Flywheel Energy Storage: Does High-Speed Really Imply a Better Design." Available via www. activepower. com (2008).
[27] Casadei, Domenico, Francesco Profumo, Giovanni Serra, and Angelo Tani. "FOC and DTC: Two viable schemes for induction motors torque control." IEEE transactions on Power Electronics 17, no. 5 (2002): 779-787.
[28] Rashed, M., and A. F. Stronach. "A stable back-EMF MRAS-based sensorless low-speed induction motor drive insensitive to stator resistance variation." IEE Proceedings-Electric Power Applications 151, no. 6 (2004): 685-693.
[29] Blaabjerg, Frede, Remus Teodorescu, Marco Liserre, and Adrian V. Timbus. "Overview of control and grid synchronization for distributed power generation systems." IEEE Transactions on industrial electronics 53, no. 5 (2006): 1398-1409.
[30] Rezaei, Navid, and Mohsen Kalantar. "Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework." Energy Conversion and Management 92 (2015): 287-301.

[31] Arani, AA Khodadoost, A. Tavakoli, G. B. Gharehpetian, and M. Seydali Seyf Abad. "Improving power sharing and reduction circulating current in parallel inverters of isolated microgrids." In Smart Grid Conference (SGC), 2013, pp. 75-79. IEEE, 2013.
[32] Rezaei, Navid, and Mohsen Kalantar. "Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework." Energy Conversion and Management 92 (2015): 287-301.
[33] Ahmadi, Saleh, Shoresh Shokoohi, and Hassan Bevrani. "A fuzzy logic-based droop control for simultaneous voltage and frequency regulation in an AC microgrid." International Journal of Electrical Power & Energy Systems 64 (2015): 148-155.
[34] Urtasun, Andoni, Pablo Sanchis, and Luis Marroyo. "State-of-charge-based droop control for stand-alone AC supply systems with distributed energy storage." Energy Conversion and Management 106 (2015): 709-720.
[35] Mehrasa, Majid, Edris Pouresmaeil, Hasan Mehrjerdi, Bo Nørregaard Jørgensen, and João PS Catalão. "Control technique for enhancing the stable operation of distributed generation units within a microgrid." Energy Conversion and Management 97 (2015): 362-373.
[36] Suvire, G. O., and P. E. Mercado. "Active power control of a flywheel energy storage system for wind energy applications." IET Renewable Power Generation 6, no. 1 (2012): 9-16.
[37] Leclercq, Ludovic, Benoit Robyns, and Jean-Michel Grave. "Control based on fuzzy logic of a flywheel energy storage system associated with wind and diesel generators." Mathematics and Computers in Simulation 63, no. 3 (2003): 271-280.
[38] Khodadoost Arani A A, B. Gharehpetian G, Zaker B. Modeling and Simulation of Flywheel Energy Storage System as V/f Reference in Islanded Microgrid. Journal of Iranian Association of Electrical and Electronics Engineers. 2016; 13 (3) :11-18.

APPENDIX A

Table A.1 Line Data of low voltage network

Line No.	R (Ω/km)	X (Ω/km)	Length (m)
1,3,6,8,10	0.284	0.038	70
4	0.497	0.1	105
5	0.462	0.077	30
7	0.87	0.083	20
11	1.38	0.085	30
2,9	3.41	0.094	10/20

Table A.2 Base load data of low voltage network

Bus Name	A	B	C	D	E	F
Load (kVA)	Main grid bus	0.250	1.8	0.2	0.4	0.5

A. A. Khodadoost Arani was born in 1991 in Iran. He received his B.Sc. and M.Sc. degrees from Electrical Engineering Department of Amirkabir University of Technology (AUT), Tehran, Iran, in 2013 and 2015, respectively. His research interests include power electronics, storage systems, power system optimization and operation, FACTS devices, and microgrids.

B. Zaker was born in Shiraz, Iran in 1989. He received the B.Sc. degree in electrical power engineering from Shiraz University, Shiraz, Iran, and the M.Sc. degree in electrical power engineering from Amirkabir University of Technology Tehran, Iran, in 2011 and 2013, respectively. He is currently pursuing the Ph.D. degree in electrical power engineering at Amirkabir University of Technology. His research interests include system identification, power system dynamics, distributed generation systems, and microgrids.

G. B. Gharehpetian (M’00–SM’08) received his Ph.D. degrees in electrical engineering in 1996 from Tehran University. As a Ph.D. student, he received a scholarship from DAAD (German Academic Exchange Service) from 1993 to 1996, and he was with High Voltage Institute of RWTH Aachen, Aachen, Germany. He has been holding the Assistant Professor position at AUT from 1997 to 2003, the position of Associate Professor from 2004 to 2007 and has been Professor since 2007. His teaching and research interest include smart grid, DGs, monitoring of power transformers, FACTS. devices, HVDC systems, and power system transients.