2017 Smart Grid Conference (SGC)

Smart/Micro Grids Research Center

Generalized droop characteristic-based Demand Response and Secondary Frequency Control Coordination in an Isolated Microgrid

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Abstract—Electricity crisis, environmental issues and as well as economic considerations enters modern power system to use alternative sources instead of the conventional ones. One of the newest ones in which controllable active and reactive loads are continuously contributed in the dynamic regulation called Demand response (DR). In this paper, a new method to apply DR in the microgrid (MG) are presented. It is based on generalized droop characteristic (GDC) which change controllable loads using a series of specific equations. The proper performance of GDC-based DR is achieved by changing controllable active and reactive loads which it changed based on the system conditions. To test the control method several scenarios are simulated in which the system frequency and voltage are studied in two states. The simulation results are carried out in the presence of conventional controller and in the next mode, in addition to the conventional ones DR is contributed in regulation dynamics. The results show that the proposed control methodology have appropriate performance such that the frequency deviations and voltage fluctuations subjected by different faults are far fewer in comparison of pervious controllers.

Keywords—Microgrid (MG), Demand response (DR), Generalized droop characteristic (GDC), smart home

I. Introduction

Frequency stability in power systems to be achieved by making balance between electrical power production and consumption. In the other words, the frequency deviation of a system which subjected by a severe disturbance is a direct result of the generation-demand imbalance. This deviation can have some adverse effects on system performance as well as network security, reliability and efficiency. A severe frequency deviation may lead to trip the power plants and even system instability, therefore it is one of the most important dynamics that should be fully evaluated, monitored and controlled. Usually, the frequency instability is occurred in the form of a continuous oscillation and can even lead to power plants blackout. Accordingly, one of the most important dynamics which should be evaluated, monitored and also, controlled is the power systems frequency [1].

The normal and emergency conditions are two major states in which frequency dynamic is studied and controlled. In the normal condition, the primary and secondary control loops regulate the system frequency while in the emergency one, under frequency load shedding (UFLS) and temporary islanding are often used [2]. An important remarkable point that exists in the all of the methods, it is non-continuous contribution of demand side in the dynamic regulation and on the system stability issues. In fact it is limited to the temporary emergency conditions. So, the suitable capabilities of the demand side contribution have not been used up to now, especially in the system frequency regulation.

In 1980, Demand Response (DR) was firstly introduced by Shweppe et al. as the ability of control and manipulate demand side loads to turn them off/on or change their consumption based on situation and in response to power quality, system security, voltage and frequency, technical and economic constraints, applied by grid operators [3]. In the fact, DR is a new search methodology to make faster balancing between generation-consumption compared to the previous studies. As well, the demand side be participated as a main and primary efforts in control loops. Furthermore, it can have many advantages as reduction of greenhouse gases emission and effects on environment, not increasing of production capacity following imbalances, energy consumption reduction, require less to the spinning reserve, fast dynamic of DR and generally, the system operation will be cheaper. Therefore, the DR as a new control methodologies can be so appropriate for systems in which there are many constraints in the production capacity including microgrids (MGs) [4]. An overall and technical review on DR contribution in coordination with the conventional frequency control loops is presented in [5]. The secure and two-way communication link between numerous light-loads and production units is one of the main challenge of DR idea which is pointed, significantly. Operating the controllable light-loads based on the frequency deviations is intended as appropriate method to meet the problem. Also, the types of demand side participation in dynamics regulation of the power systems such as the centralized and decentralized control methods is comprehensively pointed. Economic and environmental benefits of the domestic freezers and refrigerators participation in the primary frequency regulation as dynamic and flexible loads of demand side is reported in [6]. It is emphasized that if the considered study be used in the large scale can be so helpful to reduce greenhouse gases emission and adverse effects on environment. In the power system network of some countries, DR contribution improving dynamic regulation has been practically evaluated which examples of such studies and researches are mentioned in [7-9]. The distributed frequency control in smart grids via randomized DR is addressed in [10]. Based on the method, it is assumed that the considered algorithm be distributed in overall system and all of loads be intelligent and controllable. According to this, accordingly require to the centralized control unit and complex telecommunication equipment is disappeared. As well, the system frequency is exclusively regulated by randomized DR algorithm and the frequency controllers of generation side such as the governor and automatic generation control units are inactive. DR contribution Impacts on frequency of the MG systems and networks which is contained DGs and RESs in different operating conditions are studied in [11-14]. In [15-18], DR as a spinning reserve to regulate the systems frequency is considered. As well, economic advantages of DR is one of the main important feature which is surveyed in [7, 8, 19, 20]. Numerous studies on DR concept have been concentrated on connecting and disconnecting loads based on the frequency deviation thresholds as [21-23].

The DR can be applied based on the smart and innovative methods in which multiple objectives can be achieved. The present paper addresses a new approach using a coordination of the *generalized droop characteristic (GDC)-based DR and conventional frequency control loops* to better stability keep of the frequency systems. Significantly, a novel methodology which is studding and improving for such the MG systems in which most of the SGs are replaced by the RESs and DGs is adding inertia by the special methods. In the most control methods, production of the energy storage sources are changed to keep the system stability, following fault occurrences. But in the present paper, the main idea is about manipulating, turning off/on and changing of the controllable loads based on the GDC-based DR methods. In this paper, the proposed method is especially present to control the frequency dynamic, while it regulates voltage profile as well. Because, the MG system considers the DR as a new production unit which it does not exist in the traditional mode.

This paper organized as follows: Section II provides an overview on the DR coordination with frequency control loops in modern power systems. To demonstrate the effectiveness of the proposed control scheme, an islanded microgrid system is considered which In Section III, is introduced. The GDC-based DR as proposed control methodology and the require equations are presented in section III.. Several simulations for studding the performance of the applied algorithm and the results are presented in Section IV. Finally, in Section V, the conclusions are presented.

II. THE DR IN COORDINATION WITH CONVENTIONAL FREQUENCY CONTROL LOOPS

The Modern power systems as well as the MG systems require increased intelligence and flexibility in control and regulation to make certain that they are capable of maintaining a generation-load balance, following serious disturbances. This issue is becoming more considerable today because of the increasing number of MGs, as well as changing structure, environmental constraints, and the complexity of power systems. On the other hand, in the MG systems, a large part of the synchronous generators (SGs) are replaced by several the renewable energy sources (RESs) and distributed generations (DGs) such as micro turbines, photovoltaic panels, wind turbines, energy storages, fuel cells, and reciprocating engines. So, the total circulating inertia of entire system is significantly reduced which causes the system be weak following different disturbances [24, 25]. So, the conventional frequency control loops must be adopted based on the new situations. Accordingly, the DR can be a good option that can help to make sure of the power system stability.

Frequency control loops in the presence of DR are updated as shown in Fig. 1. In the generation side, RESs and DGs can contribute in the primary and secondary control loops. while in the demand side, in addition to the conventional loops there exists DR. The DR algorithm may have various inputs as system frequency and voltage, frequency and voltage deviations, power varying and so on. Also, the DR may receive some commands from the upstream units like EMS/ISO. The inputs are analyzed by the DR method and it sends a command signal (U_{DR}) to the system. It changes the amount of controllable active and reactive loads. Depending on the conditions, the active or reactive loads may contribute in the DR algorithm.

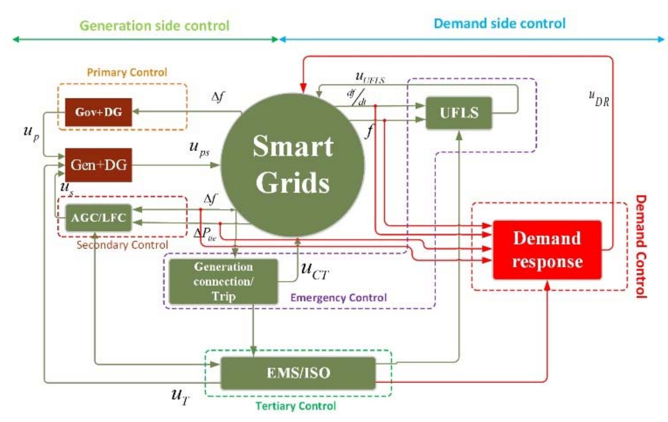


Fig. 1. Frequency control loops of the modern power systems in the presence of DR

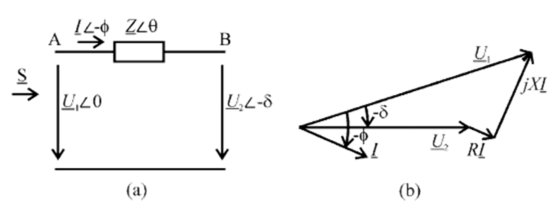


Fig. 2. (a) Power flow through a line and (b) phasor diagram

III. Generalized Droop Characteristic- Based DR

A. Active and reactive powers control based on Droop characteristic

Apparent power through a line, as shown in Fig. 2, is described [26]

$$S = P + jQ = U_1 I^* = U_1\left(\frac{U_1 - U_2}{Z}\right)^* \tag{1}$$

Thus, active and reactive power following the line are

$$P = \frac{U_1^2}{Z}cos\theta - \frac{U_1U_2}{Z}\cos(\theta+\delta) \tag{2}$$

$$Q = \frac{U_1^2}{Z}sin\theta - \frac{U_1U_2}{Z}\sin(\theta+\delta) \tag{3}$$

With $Z = R + jX$, (2) and (3) are rewritten

$$P = \frac{U_1}{R^2 + X^2}[R(U_1 - U_2\cos\delta) + XU_2 \sin\delta] \tag{4}$$

$$Q = \frac{U_1}{R^2 + X^2}[-R\, U_2 \sin\delta + X(U_1 - U_2\cos\delta)] \tag{5}$$

Generally, the system power equations are studied in the two main states. For overhead lines $X \gg R$, it means that R is Negligible. According to this, accordingly power angle δ is small, therefore $\sin\delta = \delta$ and $\cos\delta = 1$. Following the mentioned Simplification, the equations (4) and (5) became

$$\delta \cong \frac{XP}{U_1U_2} \tag{6}$$

$$U_1 - U_2 \cong \frac{XQ}{U_1} \tag{7}$$

As described in [26], the equations (8) and (9) can be respectively rewritten as (10) and (11) which show the general form of droop characteristic equations. This means that the frequency deviation is just appropriate to changes of active power as well as voltage fluctuations is depended to changes of reactive power.

$$f - f_0 = -k_P\ (P - P_0\ ) \tag{8}$$

$$U_1 - U_0 = -k_q(Q - Q_0\ ) \tag{9}$$

For non-overhead lines as distribution systems, both X and R must be considered. Thus, to simplify equations (2) and (3), an orthogonal linear rotational transformation matrix T is used. It converts P and Q to modified P' and Q' as follows.

$$\begin{bmatrix}P'\\Q'\end{bmatrix} = T\begin{bmatrix}P\\Q\end{bmatrix} = \begin{bmatrix}sin\theta & -cos\theta\\cos\theta & sin\theta\end{bmatrix}\begin{bmatrix}P\\Q\end{bmatrix} = \begin{bmatrix}\frac{X}{Z} & -\frac{R}{Z}\\\frac{R}{Z} & \frac{X}{Z}\end{bmatrix}\begin{bmatrix}P\\Q\end{bmatrix} \tag{10}$$

Applying the transformation matrix and some substitutes, a modified form of droop characteristic is achieved which shown in (13) and (14). The details are mentioned in [26, 27].

$$f - f_0 = -k_p(P' - P_0') = -k_p\frac{X}{Z}(P - P_0) + -k_p\frac{R}{Z}(Q - Q_0) \tag{11}$$

$$U_1 - U_0 = -k_q(Q' - Q_0') = -k_q\frac{R}{Z}(P - P_0) + -k_q\frac{R}{Z}(Q - Q_0) \tag{12}$$

Unlike first state, equations (13) and (14) show that the frequency and voltage deviations are depended to the both active and reactive power changes. In the other words, to frequency and voltage regulation both active and reactive power must be monitored and controlled simultaneously.

B. Generalized droop characteristic (GDC)- based DR

In most studies of DR that have been done so far, the conventional form of droop characteristic have been considered as [7, 15, 28, 29]. Generally, it is an inappropriate methodology for the microgrids because there is no overhead lines in such systems. According to the reasons mentioned, a modified form of DR is needed for the microgrid systems. This paper attempts to present a comprehensive model of DR which can be used in any systems including microgrid systems. In the following mathematical equations of generalized droop characteristic (GDC)-based DR is presented.

Considering equations of the conventional and generalized droop characteristic, there is a notable point in which frequency deviations (Δf) and voltage fluctuations (ΔV) are a function of the active and reactive power changes ($\Delta P, \Delta Q$). While, In the DR method Δf and ΔP are considered as input signals, and as well as ΔP and ΔQ are the outputs. To find ΔP and ΔQ based on Δf and ΔP equations (15) and (16) rewritten as follows

$$\begin{bmatrix}-k_p\frac{X}{Z} & -k_p\frac{R}{Z}\\-k_q\frac{R}{Z} & -k_q\frac{R}{Z}\end{bmatrix}\begin{bmatrix}\Delta P\\\Delta Q\end{bmatrix} = \begin{bmatrix}\Delta F\\\Delta U\end{bmatrix} \tag{13}$$

As described in the DR algorithm the outputs must be ΔP and ΔQ . Therefore an inversion is needed.

$$\begin{bmatrix}\Delta P\\\Delta Q\end{bmatrix} = ?$$

By inverting the matrix and, as well as finding ΔP and ΔQ based on Δf and ΔP , final form of the GDC-based DR algorithm is as equation (15).

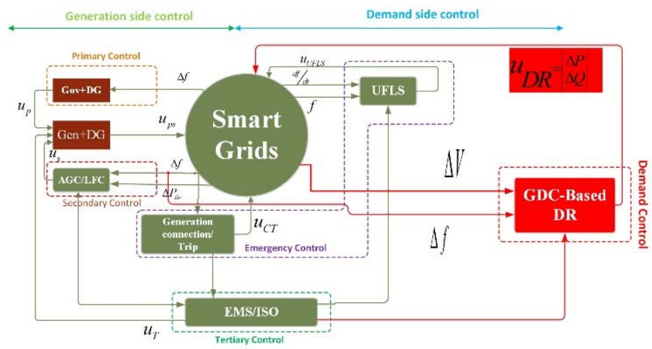


Fig. 3. The proposed DR based on GDC

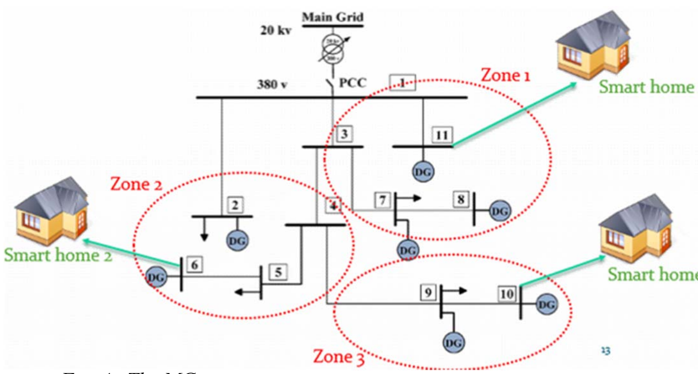


Fig. 4 . The MG test system

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix} -\dfrac{Z(\Delta U.k_p.R+\Delta F.k_q.X)}{k_p.k_q(R^2+X^2)} \\ \dfrac{Z(\Delta F.k_q.R-\Delta U.k_p.X)}{k_p.k_q(R^2+X^2)} \end{bmatrix} \tag{14}$$

Then, the main equation of GDC-based DR is given in (14). It is can be used in any systems with overhead or non-overhead lines as well. A comprehensive plan of the proposed methodology is shown in Fig. 3. As shown, in the generation side, the primary and secondary control loops by the DGs contribution are updated. Also, in the demand side in addition to the conventional UFLS, there exists a continuous participation of DR.

The proposed GDC-based DR is shown in Fig. 3. It measures Δf and ΔV of the system and send a command to it.

IV. Case Study and Simulation Results

To evaluate and test the effectiveness of the proposed GDC-based DR, an 11-bus distribution system is considered as an isolated microgrid. The Single-line diagram of test system is shown in Fig. 4. It contains four DG units which produce needed power of MG. as well, there are some controllable and non-controllable loads in the MG system. As shown in Fig. 4, the MG test system is zoned to three ones. In each zone there is a mart home which are contained several DG units, controllable and as well as non-controllable loads. The Specifications of loads in each zone are given in Table 1. It should be noted that the smart homes are capable of interrupting, connecting, and changing the controllable loads by data which received via the network. The data are generated by the proposed GDC-based DR algorithm. As an example, the loads of zone 1 are given in Table 2. As explained, a load can be considered as a contributor in the DR algorithm which connecting/disconnecting from the network be harmless to the consumers. Accordingly, the controllable loads including air conditioners, dishwashers, clothes washer and so on (Table 1) can be disconnected or connected to the network via the GDC-based DR command.

Table 1. Specifications of loads in the zones

Zone 1	Controllable loads	10 kW	4kVar
	Non-controllable loads	40+j5 (kVA)	
Zone 2	Controllable loads	15 (kW)	7 kVar
	Non-controllable loads	40+j20 (kVA)	
Zone 3	Controllable loads	5 (kW)	2 kVar
	Non-controllable loads	20+j10 (kVA)	

Table 2. Specification of Zone 1

			Appliances	Rated power (VA)
Zone 1	Controllable loads	10+j4 (kVA)	Air Conditioner	1500 +j 600
			Dishwashers	1500+j 600
			Clothes Washer	1500+j600
			Heating Coil	2000+j800
			Water Heater	2000+j800
			Refrigerators	1500+j600
	Non-controllable loads (kVA)		45+j5	

To show the performance of proposed method, several scenarios are simulated. The normal condition of MG system are shown in Fig. 5 and Fig. 6. As shown, frequency and voltage dynamic are stable.

The ratio of X/R are very effective on results, because it determines the type of power system. Therefore, it is calculated and shown in Fig. 7. It is clear that the X/R ratio is about 3. This value is considered as X/R ratio to calculate the mathematical equations and, as well as in the simulations.

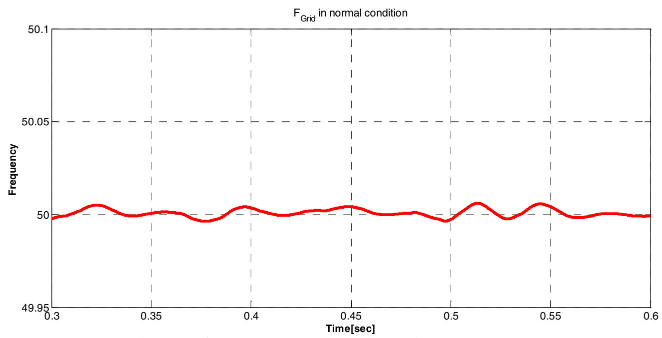


Fig. 5. The MG frequency in normal condition

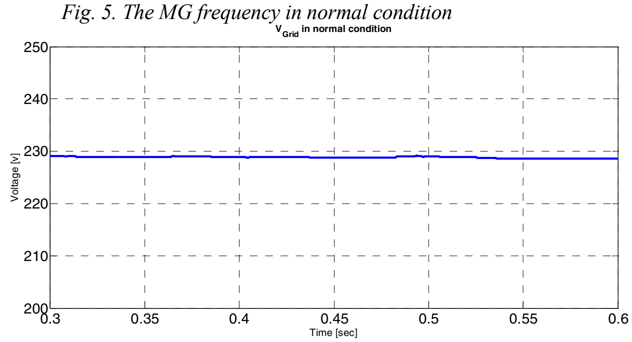


Fig. 6. The MG voltage in normal condition

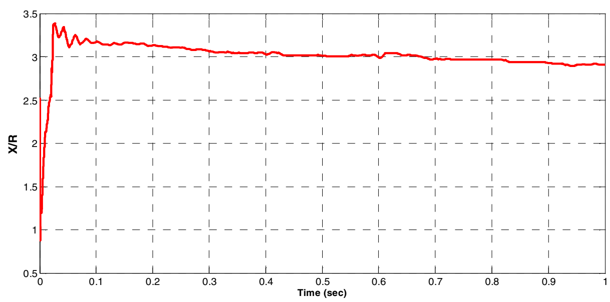
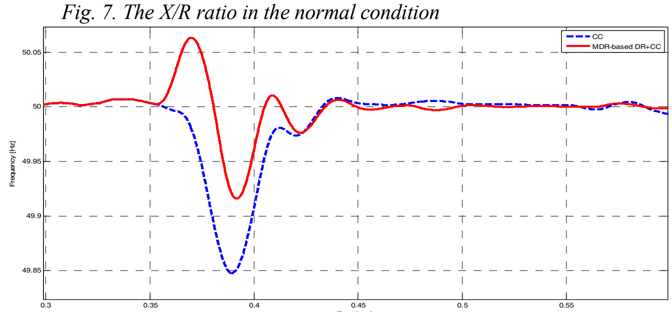
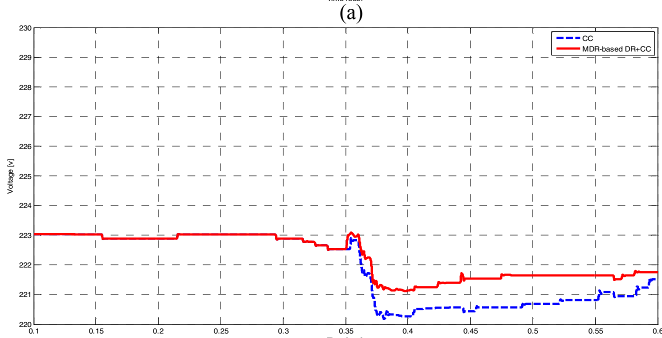


Fig. 7. The X/R ratio in the normal condition



(a)



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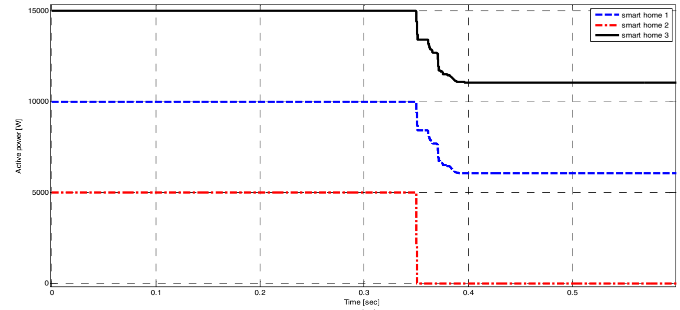

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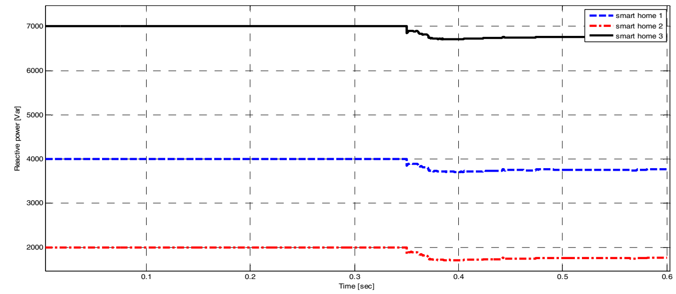


(d)

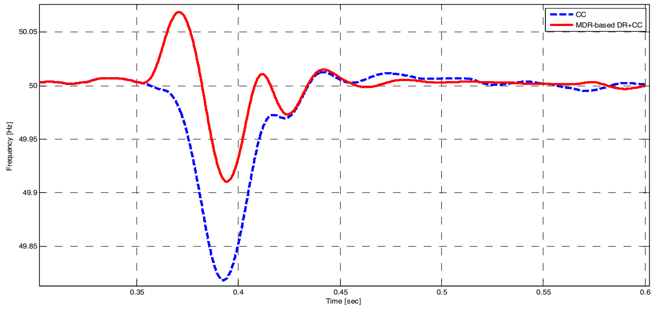
Fig. 8. A step load change; (a) the frequency system. (b) The voltage system. (c). active load change based DR. (d). Reactive load change based DR

In the simulations scenarios, frequency and voltage dynamics in the two states are compared. the blue curves show the conventional controller performance of the generation side (primary and secondary control loops) while the coordination results of GDC-based DR and secondary control loop on frequency and voltage MG are shown by red curves.

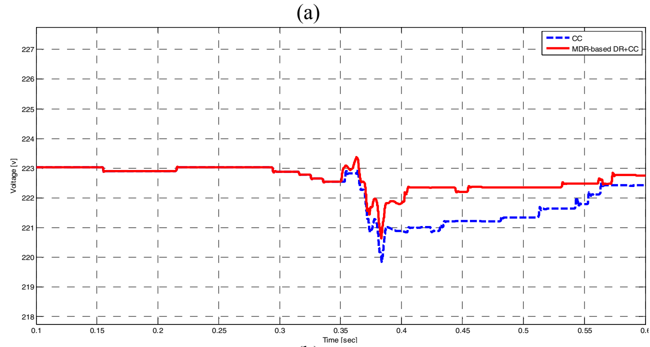
For the first scenario, a step load of 10+j5 (kVA) is suddenly occurred at time 0.35[sec]. The result of this occurrence is shown in Fig. 8 (a-d). The frequency and voltage system under two control methodology are compared and shown in Fig. 8 (a) and (b). As well the changes of active and reactive controllable loads based the proposed method are shown Fig .8 (c) and (d), respectively. The proposed GDC-based DR by changing the controllable active and reactive loads of smart homes, it regulates the frequency and voltage MG system such that be more appropriate stable in comparison of the conventional ones. The removed (changed) controllable loads can be connected to the MG system in a long time. The connecting period is determined and calculated based on system situation and GDC-based DR. Depending on the Figs. 8 (c-d), it turns out that controllable loads have a continuous contribution in dynamic regulation.

In the second scenario, impacts of a DG unit outage of 100 [kW] is studied. The simulation results are shown in Figs. 9 (a-d). Considering the results, it is cleared the appropriate performance of the proposed control methodology.

In the last scenario, impacts of a severe fault is studied. Both step load change and DG unit outage impacts on MG dynamics are checked which results are shown in Figs. 10 (a-d). As shown, by the conventional controller dynamic frequency deviations is dropped to under 0.2 [Hz]. It may cause to active the frequency relays and subsequently, the possibility of blackout even exists. While the proposed control method by contributing continuously controllable active and reactive loads, could regulate dynamic system properly in which all the stability margins are preserved, properly.



(a)



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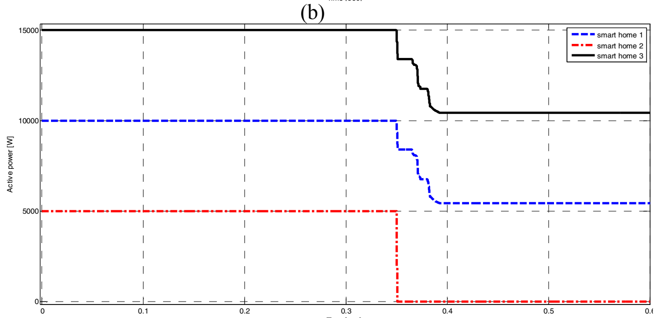

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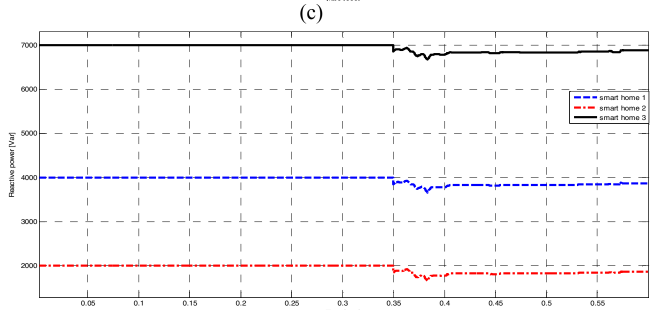
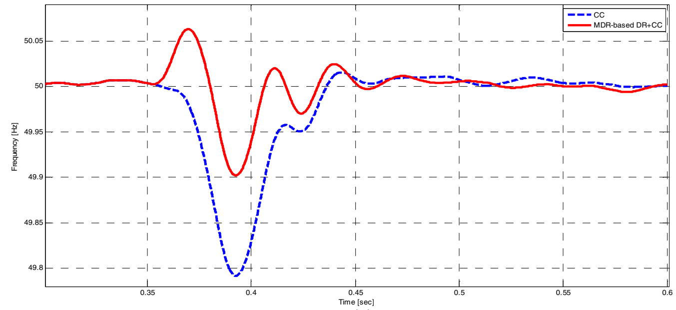


(d)

Fig. 9. A DG unit outage; (a). The frequency system. (b) The voltage system. (c). Controllable active load change based DR. (d). Controllable reactive load change based DR



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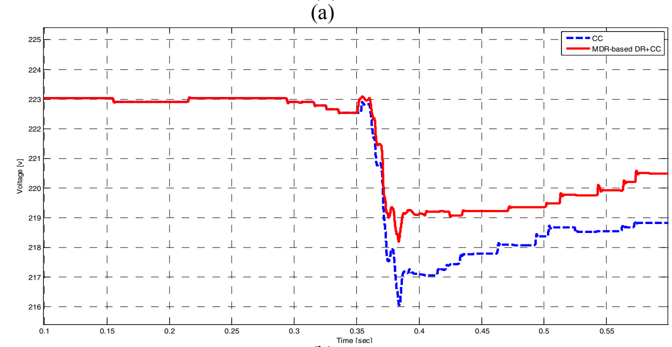

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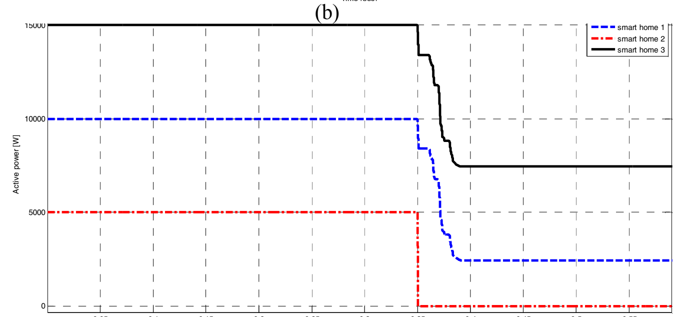

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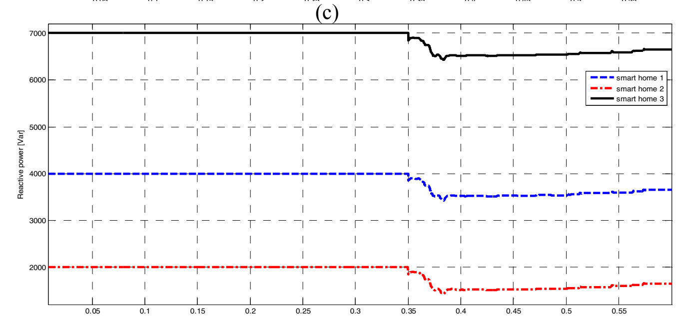

(d)

Fig. 10. Fig. 9. Impacts of A DG unit outage and step load change simultaneously; (a). The frequency system. (b) The voltage system. (c). Controllable active load change based DR. (d). Controllable reactive load change based DR

V. CONCLUSION

Electricity crisis, environmental issues and as well as economic considerations enters modern power system to use alternative sources instead of the conventional ones. The DR as a new method is introduced to modern power systems which uses the load side capabilities. In this paper, a new method to apply DR is presented which is based on GDC. The proposed methodology is generalized to any systems as transmission and distribution systems. To test the control method several scenarios are simulated in which the system frequency and voltage are studied in two states. The simulation results are carried out in the presence of conventional controller and in the next mode, in addition to the conventional ones GDC-based DR is contributed in regulation dynamics. The results show that the proposed control methodology have appropriate performance Such that the frequency deviations and voltage fluctuations subjected by different faults are far fewer in comparison of pervious controllers. The proper performance of GDC-based DR is achieved by changing controllable active and reactive loads which changed based on the system conditions.

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