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THE EFFECTS OF ADAPTIVE REPETITIVE CONTROLLER AND FEEDFORWARD ANGLE DROOP CONTROLLER WITH HIGH DROOP GAIN IN HYBRID MICROGRID WITH LOAD UNCERTAINTY AND NONLINEARITY

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Keywords: Islanded operation, Angle droop, LCL filter, Repetitive adaptive controller, High droop gain.

The present study proposes feedforward angle droop strategy based on discrete time mathematical model for islanded operation of dispatchable distributed generation (DG) units, connected directly or through voltage source converters to the microgrid. These units should supply their local and common loads. To improve the robustness of the proposed control strategy in imbalance and transient conditions, a combination of current and repetitive controller (RC), with time varying sampling period, is used. High angle droop gain ensure proper load sharing between DG units even in weak networks, but it has negative effects on grid stability. Therefore adaptive control strategy is used to solve the problems of uncertainties and also to improve the reliability of control strategy in load sharing with high angle droop coefficients. Furthermore, to reduce harmonics caused by the converters' switching, a LCL filter is used. Performance of the proposed control strategy is demonstrated for islanded microgrid, with different types of DG units, loads and conditions through simulation studies in the Digsilent Power factory software environment.

1. INTRODUCTION

Tracking a reference command is the main purpose of all controllers used in voltage source converters. Disturbances with fixed or variable periods can cause several problems in tracking references. RC can efficiently remove steady-state errors caused by disturbances with time varying / invariant period. In general, RC consist of two main parts: 1 – internal models to generate a periodic signal and 2 – compensator to stabilize the closed-loop system. Internal model, because of its ability to produce periodic signal, is a fundamental part of repetitive control. Other important part of the repetitive control is called compensation which is used to stabilize the closed-loop system.

In [1] the effects of angle droop controller on system performance has been studied under load uncertainty but the effects of increase in droop gain is not investigated. the effect of compensator type is investigated in [2]. In [3, 4] a supplementary control unit has been proposed to compensate the effects of increase in droop gain, when the controller is of angle droop type. However, the effect of the proposed controller is not studied under unbalanced or non-linear load. In [5] the effects of flexible alternating current transmission system (FACTS) devises on photovoltaic (PV) system were studied in normal and abnormal condition. The simulation of storage technologies for cutting condition were studied in [6]. But in these studies the effects of load uncertainty were not addressed.

Internal model of RC can be designed simply based on repetitive signal and sampling period, when system model and repetitive signals' period are both known. The problem arises, when a period of repetitive signal is uncertain or known, but it varies with time. These problems make RC design more complex. To solve mentioned problems, adaptive controller can be used with RC. To compensate the changes in system parameters, an adaptive repetitive controller (ADRC) scheme consists of two main steps: 1 – design repetitive compensation control based on zero phase error tracking controller in selective sampling period and 2 – controller design to maintain the closed-loop system in a selective sampling period when the sampling period is variable [7]. Reference [8] design an ADRC for linear systems under disturbances with variable period. However, the performance of the control strategy is not investigated for non-linear system. In [9] a new controller has been proposed which combines deadbeat and repetitive controller to enhance the performance of the control system in unbalanced or disturbance conditions. But, the effects of this strategy are not investigated under transient conditions. Reference [10] deals with discrete-time design of adaptive controller for voltage source converters, with LCL filter, connected to the grid. In [10] a parallel feed forward compensation has been used to shift zeroes of current controller connected to the grid. To ensure the stability and performance of network, state feedback adaptive discrete-time control system is used for various conditions. The discrete-time adaptive control can also be used to control the output voltage and power of converters with LCL filters [11]. However, these methods bring extra control difficulties such as causing the closed-loop control system to be unstable.

To control the output voltage and power of converters with LCL filters, discrete-time adaptive current control can be used. Independence of LCL filters to network characteristic's, is the main purpose of this method [11, 12] however the effects of nonlinear loads are not considered in this strategy. A powerful adaptive predictive controller for three-phase grid-connected converters presented in [13] but the impact of dynamic changes in load and line parameters is not considered. However, the effects of this controller are not tested in a multi-machine network. A digital genetic repetitive controller with harmonic order of $nk \mp m$ presented in [14] to remove / effective tracking of any frequency harmonics with $nk \mp m$ order, for constant voltage constant frequency converters with pulse width modulation. However, the design of such a controller for a multi-machine network is a very difficult task.

Impedance and frequency changes in distribution network are a challenging problem in designing converters. In [15] a frequency adaptive repetitive control scheme, in

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predefine sampling rate, has been considered to deal with all types of periodic signals with variable frequency which uses a fractional delay filter based on Lagrange's interpolation to estimate the periodic deficits. This method uses a proportional integral (PI) compensator which cannot show good performance in special cases such as transient or short circuit events.

This study focuses on problems in the standard control strategies and uses a feedforward compensation method besides ADRC to change a dynamic interplay between DG units and network when the droop gain is increased. The proposed strategy, treat like traditional droop controller; hence, it does not have any affect on power division and voltage/frequency regulation. Through changing the share of load dynamics, the network stability increases. One of the problems is the thud of load current on the operation of control system. This study uses a feedforward compensation for the elimination of internal couplings and reduction of the impact of load dynamic on control system. Under these situations, the closed loop system illustrates similar dynamic treatment under no-load and loaded conditions. This study uses the advantages of phase locked loop (PLL) unit, so the need for external frequency measurement is removed. It can also set up control strategy with unusual situation and show robust properties in different switching status. The effect of balanced, unbalanced, and nonlinear load conditions is addressed as well as sudden and random load switching incidents and short circuit event on the terminal voltage of a DG unit in islanded mode operation of a microgrid system. The details of mathematical modeling and controller design method in discrete time domain are described.

2. ISLANDED NETWORK AND DISTRIBUTED GENERATION STRUCTURE

Figure 1 illustrates a microgrid which can be used in both connected or islanded from the main grid. Network of Fig.1 consists of three types of generating units. Two of these producers are converter (dispatchable) base unit which are electrically connected to grid and the other one is a synchronous machine. Outputs of these unit are connected to main bus (PCC Terminal) through transmission lines which supply for types of load. These loads are: 1 – balanced load, 2 – motor load, 3 – unbalanced load and 4 – rectified load. Each DG unit has its own local load. In connected mode of operation, these mentioned loads can totally be provided by main grid or share between DG units and main grid.

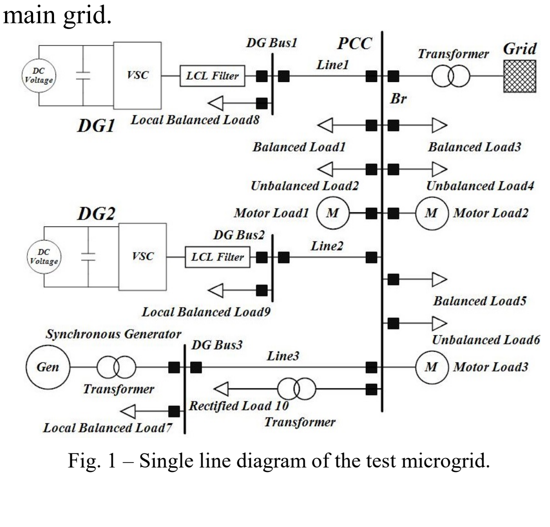

Fig. 1 – Single line diagram of the test microgrid.

Figure 2 illustrates control units of converter base DG unit. Within this controller, a three phase to two rotating d-q axis system transformation is used where θ is d axis degree of PLL output with respect to stationary axis α. The three phase variables I_{cabc},I_{gabc},V_{Cabc},V_{Cfabc},V_{tabc} respectively signify the converter, network side current of LCL filter, converter side, capacitor voltage of LCL filter and PCC Terminal voltage.

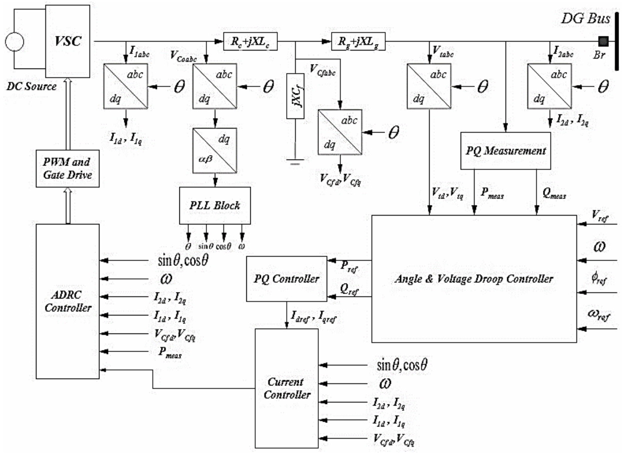

Fig. 2 – Control unit of converter base DG.

To generate a reference angle, (1) can be used [16]

$$\varphi^* = \left(\omega_S - (m \times P) - \omega_{PCC}\right) {}^{K_I}\!/_{S} + {}^{\omega_{PCC}}\!/_{S} , \qquad (1)$$

where Φ*, ω_s, ω, PCC terminal, m, P and K_I represents reference angle, measured frequency, reference frequency, droop coefficient, measured active power and integral factor respectively. Angle and voltage droop controller blocks, produce active and reactive power references based on (2)

$$\begin{aligned} \delta &= \delta_{Rated} - m\left(P_{Rated} - P\right) \\ V &= V_{Rated} - n\left(Q_{Rated} - Q\right) \end{aligned} , \qquad (2)$$

where δ_{Rated}, δ, P_{Rated}, P, Q_{Rated}, Q, V_{Rated},V and m, n show the reference angle, the produced angle, the reference and measured active and reactive power, the reference and measured voltage and droop coefficient respectively. The outputs of the block are then sent to PQ controller unit to produce reference currents for current control unit. To enhance the performance of the control system with high droop gain and harmonic elimination, outputs of this block are sent to ADRC unit to produce signal by phase locked loop (PLL) block. In order to optimize the load sharing between multiple DG units, their droop coefficients must be increased [3, 17, 18]. Nevertheless, it has an adverse influence on overall stability. To solve this problem in [17, 18] different types of method have been proposed. However these solutions assumed existence of data about control system, network and DG units with L filter type.

3. CURRENT ANGLE DROOP CONTROL STRATEGY WITH LCL FILTER

The current control strategy includes the core shown in Fig. 2. The main purpose of the current controller is current components' tuning at the ac-side of voltage source converter (VSC) by means of pulse width modulation. To analyze how the required pulses are produced in discrete time domain, the method expressed in [1] can be used.

4. **ADAPTIVE REPETITIVE CONTROL DESIGN**

4.1. MODEL OF VOLTAGE SOURCE CONVERTER WITH LCL FILTER

This part express a method to solve the problem of uncertainty in load or system parameters. Figure 5 illustrates a simplified model of the VSC and its LCL filter. To make a minimum phase system, the resistance should be considered in this model. In order to design filter parameters the method expressed in [19] can be used and also to reduce the complexity of the design process, a three phase to two stationary αβ axis transformation is used. In Fig. 5, u is output of voltage source converter and it is one of the design parameters. r_c, L_c and r_g, L_g respectively represent the resistance and inductance of converter and grid side of the LCL filter. According to Fig. 3 a complete knowledge of designed filter are known. However, the inductance of $L_{gT} = L_g + L_{gg}$ (L_g, L_{gg} are converter side and overall grid side inductance of filter) due to uncertainty in L_{gg} is unknown. To solve the problems of uncertainty in line parameters and load uncertainty, adaptive controller can be used. To remove disturbances, due to uncertainty in disturbance period, RC can be used.

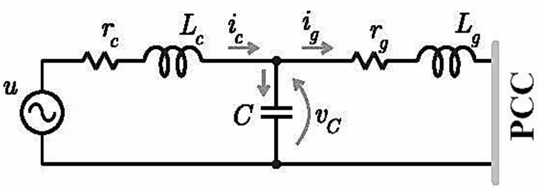

Fig. 3 – A simplified model of source with LCL filter [1]

4.2. STATE FEEDBACK ADAPTIVE REPETITIVE CONTROL

The main objectives of this controller are: 1 – stable control of system, 2 – disturbance elimination and 3 – stable operation of DG units in transient conditions. The parameters and the design process of the controller will be stated in following sections. To begin the process of designing an adaptive controller, it is necessary to obtain discrete-time state equations of the plant according to continuous- time state equations.

$$\begin{bmatrix} \dot{i}_c \\ \dot{i}_g \\ \dot{v}_c \end{bmatrix} = \begin{bmatrix} -\frac{r_c}{L_c} & 0 & -\frac{1}{L_c} \\ 0 & -\frac{r_g}{L_g} & -\frac{1}{L_g} \\ \frac{1}{C} & -\frac{1}{C} & 0 \end{bmatrix} \begin{bmatrix} i_c \\ i_g \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L_c} \\ 0 \\ 0 \end{bmatrix} u,$$

$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_c \\ i_g \\ v_c \end{bmatrix}, \qquad (3)$$

where v_c, i_g, i_c represent the state variables and u, y represent the input and the output signals. In (3), grid converter side current can be chosen as output of the model. One deduces the discrete time model of (3). Where A_d, B_d and C are parameters of state equation in discreet time.

$$A_d = \begin{bmatrix} 1-\frac{Tr_c}{L_c} & 0 & -\frac{T}{L_c} \\ 0 & 1-\frac{Tr_g}{L_g} & -\frac{T}{L_g} \\ \frac{T}{C} & -\frac{T}{C} & 0 \end{bmatrix},$$

$$B_d = \begin{bmatrix} \dfrac{r_g + L_c\left(\frac{r_c}{L_c}-1\right)}{L_c\left(r_c+r_g\right)} \\ \dfrac{r_c + L_c\left(\frac{r_c}{L_c}-1\right)}{L_c\left(r_c+r_g\right)} \\ -\dfrac{r_c r_g + L_c L_g\left(\frac{r_c}{L_c}-1\right)}{L_c\left(r_c+r_g\right)} \end{bmatrix} C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}. \qquad (4)$$

The discrete-time system transfer function can be obtained as follows

$$G(z) = C(zI - A_d)^{-1} B_d = k_p \frac{Z(z)}{P(z)}. \qquad (5)$$

In (5) k_p,$Z(z)$ and $P(z)$ are given by

$$k_p = -\frac{T}{L_C},\ Z(z) = Z_2 - 2Z + \left(1+\frac{T^2}{CL_g}\right)$$
$$P(z) = Z^3 - 3Z^2 + Z\left(3+\frac{T^2}{CL_g}+\frac{T^2}{CL_C}\right) - \left(1+\frac{T^2}{CL_g}+\frac{T^2}{CL_C}\right). \qquad (6)$$

To design an adaptive state feedback model reference controller which ensure perfect tracking of reference signal, assumptions given in [20] are considered.

Perfect reference model output tracking is the ultimate goal of adaptive controller. This can be obtained from linear time invariant model as follows

$$y_m(k) = W_m(z) r(k), k \in \{0,1,2,\ldots\}, W_m(z) = \frac{k_m}{P_m(z)}. \qquad (7)$$

In (7), $P_m(z)$ is a stable polynomial of degree n^* and can be defined as $P_m(z)=Z^n$. The model reference adaptive control for convenient tracking of reference signal, can be expressed as follows

$$u(k) = k_1^{\mathrm{T}}(k)x(k) + k_2(k)r(k), \qquad (8)$$

where $r(k)$ indicates reference signal and $k_1(k) = \left[k_{11}(k), k_{12}(k), \ldots, k_{1n}(k)\right]^{\mathrm{T}} \in R^n, k_2(k) \in R$ are adaptive estimated values of unknown parameters $k_1^* = \left[k_{11}^*, k_{12}^*, \ldots, k_{1n}^*\right]^{\mathrm{T}} \in R^n, k_2^* \in R$. The values of the unknown parameters can be obtained by

$$\det(zI - A_d - B_d k_1^{*\mathrm{T}}) = P_m(z) Z(z) \frac{k_m}{k_p},\ k_2^* = \frac{k_m}{k_p}. \qquad (9)$$

(9) indicates that all zeroes of $\det(zI - A_d - B_d k_1^{*\mathrm{T}})$ are stable. The ideal copy of (8) which lead to ideal output of closed-loop system $y(z)=W_m(z)r(z)$, can be defined as

$$u(k) = k_1^{*\mathrm{T}}(k)x(k) + k_2^*(k)r(k)\,. \tag{10}$$

The ideal control gain k_1^*, k_2^* are unknown when the *A, B,C* matrixes of (3) are unknown. Therefore an adaptive law is required to update the estimated parameters of k_1,k_2. From (10) one deduces

$$C\left(zI - A_d - B_d k_1^{*\mathrm{T}}\right)^{-1} B_d k_2^* = \frac{Z(z)k_2^*}{\det\left(zI - A_d - B_d k_1^{*\mathrm{T}}\right)} = \frac{1}{P_m(z)} = W_m(z). \tag{11}$$

The values for k_1^*, k_2^* can be obtained as follow

$$k_{11}^* = \frac{LC}{T}, k_{12}^* = 0,\; k_{13}^* = 1,\; k_{14}^* = 1\,. \tag{12}$$

Based on (8) – (11) the tracking error equation can be defined as

$$\begin{aligned} e(k) &= y(k) - y_m(k) \\ e(k) &= \rho^* W_m(z)\left[\left(k_1^{\mathrm{T}} - k_1^{*\mathrm{T}}\right)x + \left(k_2 - k_2^*\right)r\right](k)\,, \\ &\quad + C\left(A_d + B_d k_1^{*\mathrm{T}}\right)^{t} x(0), \end{aligned} \tag{13}$$

where $\rho^* = k_p$ and $C\left(A_d + B_d k_1^{*\mathrm{T}}\right)^{t} x(0)$ exponentially converges to zero.

4.3. ADAPTIVE LAWS

To obtain the estimation error ε(k), the following signals are considered

$$\begin{aligned} \theta(k) &= \left[k_1^T(k), k_2^T(k)\right]^{\mathrm{T}},\; \theta^* = \left[k_1^{*\mathrm{T}}, k_2^{*\mathrm{T}}\right] \\ \omega(k) &= \left[x_1^{\mathrm{T}}(k), r(k)\right]^{\mathrm{T}},\; \eta(k) = W_m(z)[\omega](t) \\ \xi(k) &= \theta^{\mathrm{T}}(t)\eta(k) - W_m(z)\left[\theta^{\mathrm{T}}\omega\right](k). \end{aligned} \tag{14}$$

Based on (13) and (14) one deduces

$$\varepsilon(k) = e(k) + \rho(k)\xi(k)\,, \tag{15}$$

where ρ(k) is the estimate of ρ*= k_p. It then follows from (14) and (15) that

$$\varepsilon(k) = \rho^*\left(\theta(k) - \theta^*\right)^{\mathrm{T}}\eta(k) + \left(\rho(k) - \rho^*\right)\xi(k)\,. \tag{16}$$

Considering gradient error method [20], the following adaptive laws are recommended for θ(k) and ρ(k).

$$\begin{aligned} \theta(k+1) &= \theta(k) - \frac{\mathrm{sign}\left[\rho^*\right]\Gamma\eta(k)\varepsilon(k)}{m^2(t)}, 0 < \Gamma = \Gamma^{\mathrm{T}} < \frac{2}{k_p^0} I_{n+1} \\ \rho(k+1) &= \rho(k) - \frac{\gamma\xi(k)\varepsilon(k)}{m^2(k)},\quad 0 < \gamma < 2\,, \end{aligned} \tag{17}$$

where $k \in \{0,1,2,...\}$ and sign(ρ*) represents sign of parameter ρ*, $\Gamma \in R^{(n+1)\times(n+1)}$ are constant adaptive gains and $m(t)$ can be defined as follows

$$m(k) = \sqrt{1 + \eta^T(k)\eta(k) + \xi^2(k)}\,. \tag{18}$$

4.4. REPETITIVE CONTROLLER

Repetitive control has proven to be an effective strategy to track/reject a repetitive input signals. So to enhance the capability of disturbance rejection, this paper combine ADRC strategy and angle droop controller. Figure 5 illustrates the overall block diagram of an ADRC to control the voltage source converter.where $F(z) = k_r Z^m$ represents compensator block [21]. k_r, m indicate the RC gain and the lead step respectively. To ensure system stability k_r=1, m=1 can be chosen. In Fig.4, Z^{N} related to N step delay on signal where $N = T/T_s$ represents the ratio of the disturbance input period to the sampling period. In this paper, the delay value (N) is considered to be 4. To keep N constant, the sampling period is locked to the disturbance period. First order Q(z) filter, in most repetitive controller design, normally provide an appropriate response [21]. Therefore filter Q(z) can be chosen as $Q(z) = 0.25Z + 0.5 + 0.25Z^{-1}$.

5. CASE STUDY AND THE RESULTS OF THE SIMULATION

To demonstrate the effectiveness of the proposed control strategy, Fig. 1 with switching details has been simulated in Digsilent Power factory environment. The microgrid of Fig. 1 can be used in both islanded or grid connected mode of operation. In grid connected mode, DG units can provide entire, a portion or none of their connected loads while in islanded mode, the DG units are responsible for provision of demand power as well as maintaining voltage and frequency of microgrid. This is done by control section of the DG units which is discussed in Sections 3 and 4.
Parameters of lines and the DG units used in the microgrid of Fig.1 are presented in Table 1. The design parameters of LCL filter which is designed by procedure expressed in [19], are given in Table 2.

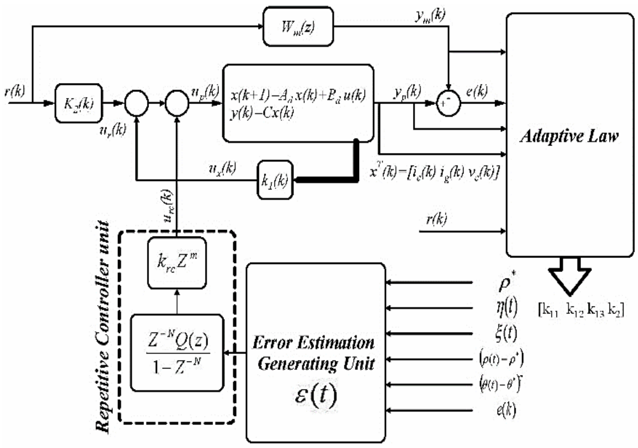

Fig. 4 – Overall adaptive repetitive controller.

Table 1

Parameters of lines and DG units used in microgrid

DG parameters			
Parameter	**DG #1**	**DG #2**	**DG #3**
m (p.u)	0.167	0.2	0.1333
n (p.u)	0.333	0.4	0.267
S (kVA)	120	100	150
Voltage (V)	400	400	200
Line parameter	**Line**	**Line 1**	**Line 2**
R(Ω/km)	0.1	0.1	0.1
X_L(Ω/km)	0.02	0.02	0.02
Length(km)	2	3	4
Voltage(V)	400	400	400

Table 2
Design parameters of LCL filter

Parameter	Remark	Value	
f_g	Grid frequency	50 Hz	
f_{SW}	Switching frequency	10 kHz	
LCL Filter		DG #1	DG #2
L_C (mH)	Converter-side inductance	0.68	0.817
L_g (μH)	Grid-side inductance	15.91	19.12
C_f	Filter capacitance	95.5	79.5
R_f	Damping resistance	0.1345	0.162

Loads connected to microgrid of Fig. 1 consist of balanced three-phase load, unbalanced, rectified, induction motor and local loads. Values for each loads are given in Table 3. In Fig. 1, each of the DG units have their own local loads which can be provided by their own producers or divided between DG units according to their droop coefficient. In this paper the latter is selected.

Table 3
Active and reactive load values of microgrid

		P(kW)	Q(kvar)
Balanced load1		22	4
Balanced load3		30	5
Balanced load5		30	15
M1,M2,M3		3	4
Local load7		30	10
Local load8		10	5
Local load9		10	5
Load2	Phase a	10	5
	Phase b	0	0
	Phase c	15	6
Load4	Phase a	0	0
	Phase b	10	6
	Phase c	17	4
Load6	Phase a	10	5
	Phase b	18	8
	Phase c	0	0
Rectified load		40	5

In the case studies, the balance loads are connected to the microgrid from the start up time of simulation and all loads of microgrid, in connected mode, are provided by the main grid. At t = 5 s, the loads are provided by the DG units based on their droop coefficients. The series of events surveyed in this microgrid are given in Table 4. These events have been chosen to show the behavior of the proposed control strategy.

Table 4
Series of events investigated in microgrid

Item	Event type	Time of event (s)
1	Disconnecting from main grid	5
2	Operation of controller to control voltage and frequency	5
3	Connecting rectified load	50
4	Connecting motor loads (M1,M2,M3)	80
5	Connecting Load2 & Load4 & Load6	140
6	Short circuit event in line 1	200
7	Disconnecting Line 1 from the microgrid	200.07
8	Disconnecting unbalanced Load 2	250
9	Disconnecting unbalanced Load 4	280
10	Disconnecting unbalanced Load 6	300
11	Disconnecting rectified Load	320
12	reconnecting Line 1 to microgrid	450
13	Connecting local Load7	550
14	Connecting local Load8	600
15	Connecting local Load9	650

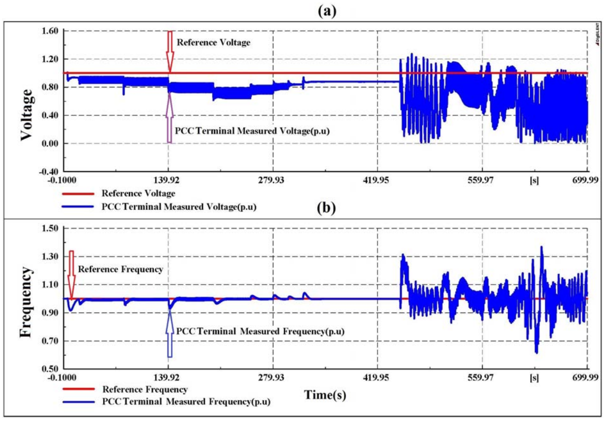

Fig. 5 – PCC terminal reference and measured a-voltage b-frequency without ADRC (adaptive repetitive controller).

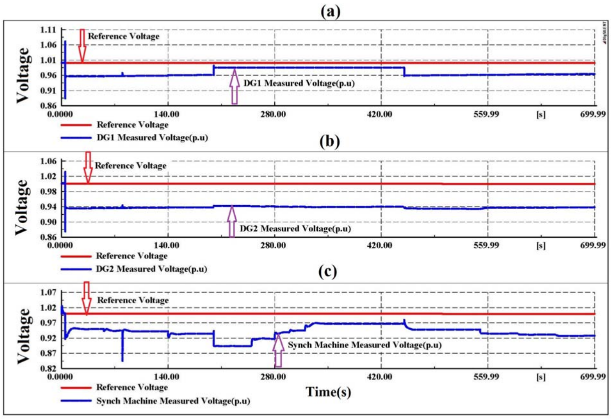

Fig. 6 – Generated voltage of DG units a- DG #1 b-DG#2 c-synch generator.

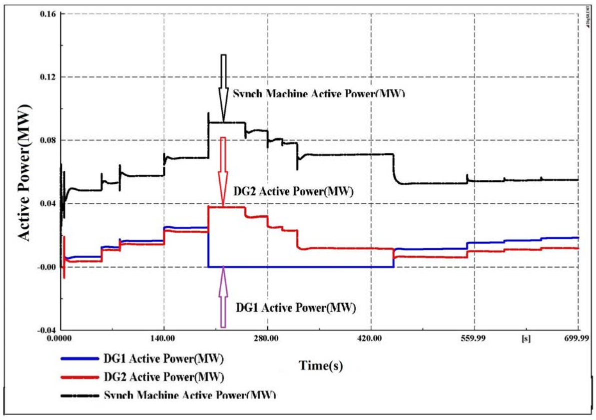

Fig. 7 – Active power sharing between DG units.

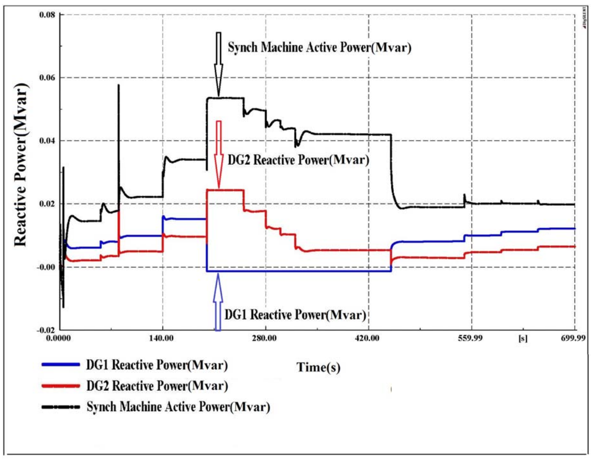

Fig. 8 – Reactive power sharing between DG units.

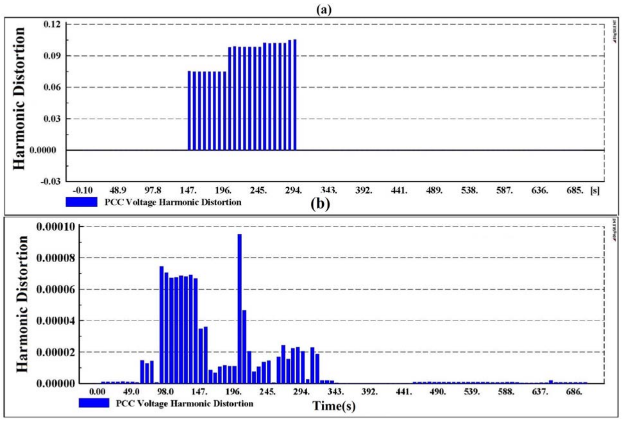

Fig. 9 – Total harmonic distortion of PCC terminal voltage a-without adaptive repetitive controller (ADRC) b-with ADRC.

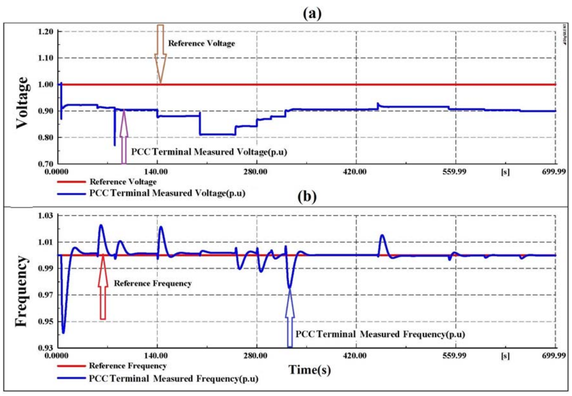

Fig. 10 – The overall PCC terminal voltage and frequency in different condition.

5.1. SYSTEM RESPONSE IN THE PRESENCE OF CONVENTIONAL ANGLE DROOP CONTROLLER WITH HIGH DROOP GAIN COEFFICIENTS

In order to have an optimized load sharing between the DG units of Fig. 1, droop coefficients will be increased. In this case, as Fig. 5 shows, the network becomes unstable. To solve this problem, the ADRC can be used with angle droop controller.

5.2. SYSTEM RESPONSE TO MODE TRANSFER OF MICROGRID

According to Table 1 at t = 5 s, a transition will be occurred from grid connected to islanded mode of operation. This will be happened by triggering the coil of the Br switch. In islanded mode of operation, the DG units have to provide microgrid demands as well as regulating frequency and voltage of grid under different condition. During transition from grid connected to islanded mode, only balanced loads are connected to the grid. As Fig. 6 shows, at t = 5 s the voltage and frequency of DG units will be forced to track their respective references stable and at appropriate speed. Also Figs. 7 and 8 show active and reactive power sharing between DG units. As these figures show, the active and the reactive power are divided between DG units based on the DG units' droop coefficients.

5.3. RESPONSE TO LOAD CURRENT DISTURBANCE

One kind of load considered in Fig.1 is a rectified load. It should be noted that at this time, the balanced loads are still connected to the grid. Due to thyristor switching, total harmonic distortion (THD) of voltage and current at PCC Terminal bus will be increased. Figures 9 a and b respectively show THD of PCC terminal voltage with common angle droop controller with low droop gain and proposed ADRC and high droop gain. As Fig. 9 shows, the average THD of PCC terminal voltage is about 0.8 % which is lower than normal THD.

5.5 RESPONSE TO SHORT CIRCUIT EVENT

At t = 200 s a three-phase short circuit occurs at the line connected to DG unit#1 while the loads mentioned in Section 1–4 are still connected to the grid. This transmission line is disconnected from the grid after 0.07 seconds (*i.e.* t = 200.07 s) which result in isolating the DG unit #1 from the grid. From t = 200.07 s, power demand and maintaining the voltage and frequency of the grid are provided through DG units #2 and #3. Figure 10 illustrates the overall PCC terminal voltage and frequency of PCC terminal.

6. **CONCLUSION**

The current study, aimed to a voltage and angle control strategy for dispatchable DG units connected directly and electrically to the network. The performance of proposed control strategy is improved by utilizing a combination of feedforward angle droop controller and adaptive repetitive controller. Repetitive controller can efficiently remove the steady-state errors caused by disturbances with time varying / invariant period. Therefore voltage and frequency regulation will be improved. In order to solve the problem of load sharing with high angle droop gain and uncertainties in load and system parameters, adaptive controller can be used. Also a LCL type filter is used to filter the harmonics produced by the converter. Also in this paper, the effect of local loads on each of the DG unit buses, were also investigated. Studies conducted on the overall system shown that the proposed strategy illustrate effective performance in different conditions such as unbalanced loads, load current disturbance, transient conditions and sharing of loads between different types of DG units.

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REFERENCES

1. M. S. K. Niya, A. Kargar, S. Y. Derakhshandeh, *Effects of an Angle Droop Controller on the Performance of Distributed Generation Units with Load Uncertainty and Nonlinearity*, Journal of Power Electronics, **17**, *2*, pp. 551–560, March, (2017).
2. M. S. K. Niya, A. Kargar, S. Y. Derakhshandeh, *Effects of angle droop and controller type in hybrid microgrid with load uncertainty and nonlinearity*, *Revue Roumaine des Sciences Techniques-serie Electrotechnique et Energetique,* **62**, *3*, pp. 233–239, (2017).
3. R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, *Improvement of Stability and Load Sharing in an Autonomous Microgrid Using Supplementary Droop Control Loop*, IEEE Transactions on Power Systems*,* **25**, *2*, pp. 796–808, (2010).
4. A. Ketabi, M. Soltanfar, *A Control Method for Autonomous Microgrid in High Droop Gains*, International Journal of Mechatronics, Electrical and Computer Technology(IJMEC)*,* **6**, *20*, pp. 2856–2871, Apr, 2016.
5. R. Vatu, O. Ceaki, N. Golovanov, R. Porumb, and G. Seritan, *Analysis of storage technologies within smart grid framework*, 9th International Universities Power Engineering Conference (UPEC), pp. 1–5, (2014).
6. R. Vatu, O. Ceaki, M. Mancasi, R. Porumb, G. Seritan, Power quality issues produced by embedded storage technologies in smart grid

environment, 9th International Universities Power Engineering Conference (UPEC), pp. 1–5.

7. J. M. Olm, G. A. Ramos, R. Costa-Castelló, *Adaptive compensation strategy for the tracking/rejection of signals with time-varying frequency in digital repetitive control systems*, Journal of Process Control, **20**, pp. 551–558, 2010.
8. E. Kurniawan, Z. Cao, Z. Man, *Digital design of adaptive repetitive control of linear systems with time-varying periodic disturbances*, IET Control Theory & Applications, **8**, *17*, pp. 1995–2003,(2014).
9. M. B. Delghavi, A. Yazdani, *Islanded-Mode Control of Electronically Coupled Distributed-Resource Units Under Unbalanced and Nonlinear Load Conditions*, IEEE Transactions on Power Delivery, **26**, *2*, pp. 661-673, (2011).
10. J. R. Massing, H. Pinheiro, *Adaptive Current Control of Grid-Connected VSC with LCL-Filters using Parallel Feedforward Compensation*, 36th Annual Conference on IEEE Industrial Electronics Society, pp. 3185–3191, (2010).
11. J. R. Massing, M. Stefanell, H. A. Gründling, H. Pinheiro, *Adaptive current Control for Grid-Connected Converters with LCL Filter*, IEEE transactions on industrial electronics, **59**, *12*, pp. 4681–4693, (2012).
12. J. R. Massing, H. Pinheiro, *Adaptive current control of grid-connected VSC with LCL-filters using parallel feedforward compensation*, 36th Annual Conference on IEEE Industrial Electronics Society, pp. 3185–3191, (2010).
13. J. M. Espi, J. Castello, R. Garcia-Gil, G. Garcera, E. Figueres, *An adaptive robust predictive current control for three-phase grid-connected inverters*, IEEE Transactions on Industrial Electronics, . **58**, *8*, pp. 3537–3546, (2011).
14. W. Lu, K. Zhou, D. Wang, M. Cheng, *A generic digital-order harmonic repetitive control scheme for PWM converters*, IEEE Transactions on Industrial Electronics, **61**, *3*, pp. 1516–1527, 2014.
15. R. Nazir, K. Zhou, N. R. Watson, A. Wood, *Frequency adaptive repetitive control of grid-connected inverters*, 2014 International Conference on Control, Decision and Information Technologies (CoDIT), pp. 584–588, (2014).
16. N. Pogaku, M. Prodanovic, T. C. Green, *Modeling*, *Analysis and Testing of Autonomous Operation of an Inverter-Based Microgrid*, IEEE Transactions on Power Electronics, **22**, *2*, pp. 613–625, (2007).
17. R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, *Operation and Control of Hybrid Microgrid with Angle Droop Controller*, IEEE Region 10 Conference, pp. 509–515, (2010).
18. R. Majumder, A. Ghosh, G. Ledwich, F. Zare, *Angle Droop versus Frequency Droop in a Voltage Source Converter Based Autonomous Microgrid*, PES '09, IEEE Power & Energy Society General Meeting, pp. 1–8, (2009).
19. A. Reznik, M. G. Simões, A. Al-Durra, S. M. Muyeen, *LCL Filter Design and Performance Analysis for Grid Interconnected Systems*, IEEE Transactions on Industry Applications, **50**, *2*, pp. 1225–1232, (2014).
20. G. Tao, *Adaptive control design and analysis*, John Wiley & Sons, (2003).
21. B. Zhang, D. Wang, K. Zhou, Y. Wang, *Linear phase lead compensation repetitive control of a CVCF PWM inverter*, IEEE Transactions on Industrial Electronics, **55**, pp. 1595–1602, (2008).