A COMMUNICATION-FREE SIGNAL GENERATING TECHNIQUE FOR REACTIVE POWER CORRECTION IN ISLANDED MICROGRID

Nashitah Alwaz[1], Safdar Raza[1*], Sadaqat Ali[1]

ABSTRACT

The primary function of microgrid (MG) is to share the power accurately among different distributed generation (DG) units according to the load demands. The droop control methods are normally used for appropriate power sharing. However, these control techniques suffer badly due to the feeder impedances and uncontrollable power coupling issues. Many techniques have been proposed to share power accurately, most of them rely on communication link. In this work a localized/communication free signal generating mechanism is proposed. The mechanism injects the transient reactive power in frequency droop characteristics by observing the changes in microgrid. This injection disturbs the actual active power sharing which is helpful for the computation of reactive power sharing errors. These errors are minimized by utilizing the proportional integral (PI) controller. The PI controller modifies the y-intercept and the slop of Q-E (Reactive Power –Voltage) droop characteristic for the correction of reactive power sharing error. Moreover, the parameters of droop and PI controller of inner control loop are optimized by Particle Swarm Optimization (PSO) to obtain high precision and reliability. The proposed technique has the following salient features:

Accurately shares the reactive power without the information of feeder line impedances/ This accurate reactive power sharing scheme has been started locally without the need of communication signal from the central controller. Thus, there is no delay in monitoring the notable changes in microgrid caused by DGs. The careful selection of PI & droop controller parameters through PSO makes the system more stable as compared to the conventional methods in terms of transients and steady state responses.

KEYWORDS: *Decentralized Control, Distributed Generation (DG), Droop Control, Microgrid Control, Power Sharing, Particle Swarm Optimization (PSO)*

INTRODUCTION & RELATED WORK

Conventional electrical power networks are facing difficulties due to exponential rise in consumer demands and environmental issues/problems. Recently, distributed generation (DG) has gained a lot of consideration to fulfil high electricity demands, consolidate more renewable power resources and to lessen the stress on the current power transmission and distribution networks. A microgrid (MG) network normally consists of cluster of interconnected loads and parallel connected DG units. The unique feature of the MG is its competency to operate in two different modes; grid connected and islanded mode. Islanded mode can be occurred intentionally (scheduled) or unintentionally (Sen and Kumar, 2018).

In an islanded mode, power should be appropriately shared among different types of DG units. Normally, droop control technique has been deployed for the sharing of real and reactive power between DGs. It is a popular technique because of its independency on the communication signals among DG units (Nutkani, Loh and Blaabjerg, 2014), (Khaledian and Aliakbar Golkar, 2017). The active power has been appropriately shared among DG units at the steady state level. However, it fails to share the reactive power accurately due to some difficulties (Han et al., 2016). As opposed to the frequency, voltage is a local parameter in the MG network. Moreover, the reactive power is influenced by the mismatches in feeder impedances (Eid et al., 2016), (Rajesh et al., 2017). Furthermore, conventional droop control method is sensitive for resistive line impedances in low voltage (LV) microgrid. Therefore, the coupling among the reactive and real powers of DG units become a challenge for accurate reactive power sharing (Olivares et al., 2014). The inaccurate reactive power sharing in an islanded MG can produce frequency and voltage fluctuations, poor power quality and unplanned load curtailment which ultimately disturb the stability of the MG network (Han et al., 2016).

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Different control strategies have been proposed in literature for accurate sharing of reactive power. However, some techniques depends on the physical parameters of the system (Dou et al., 2017),(Hu et al., 2018),(Liu et al., 2017), some require a difficult computation process (Zhu et al., 2016), and some of them uses communication signal for the triggering of reactive power correction scheme (Gao et al., 2018), (Lu et al., 2017), (Zhang et al., 2017), (Zhou et al., 2018). These control strategies bear some functional difficulties which needs to be resolved: Firstly, some reactive power correction schemes require information of physical parameters. Secondly, utilizing the communication links degrade the reliability of the MG network. Any spontaneous delay or failure in information transmission disturbs the execution of the proposed strategies. Thirdly, the correction process of the Q-E (Reactive Power –Voltage) droop control method is slow and inaccurate to produce output fluctuations among DG units. Fourthly, the stability of the microgrid is extremely affected by the poor selection of voltage, current & droop control parameters due to some significant constraints.

This research work improves reactive power sharing and system stability by exploiting these salient features: Firstly, a synchronized reactive power correction scheme is established which is not influenced by the information of physical parameters. Secondly, a localized decision-making topology is deployed to activate the reactive power correction scheme without utilizing any communication link among DG units. Thirdly, localized decision-making technique accurately triggers the controller against any perceptible variation in DG units operating point. Lastly, the optimal selection of the droop and Proportional integral (PI) controller parameters is done by particle swarm optimization (PSO).

Related Work

To acquire accurate reactive power sharing, modified different droop control techniques has been presented/ addressed. For instance, virtual structure based topologies has been proposed which compensate the difference among output impedances and needs a controller for the virtual voltage drop estimation (Afshar et al., 2019), (Hu et al., 2015). However, these droop techniques face the issue of voltage and frequency deviations in critical loading conditions. A new topology based on the phenomena of negative resistance has been presented for adequate sharing of reactive power but, this topology requires the information of line parameters which is a complicated process (Dou et al., 2017). Another wireless reactive power correction scheme has been presented in (Zhu et al., 2016). This topology utilizes the genetic algorithm for the calculation and elimination of reactive power sharing error. Although technique accurately shares the power, but it requires a long computation process. Recently, some researches has been suggested based on improved adaptive virtual impedance control strategy (Hoang and Lee, 2018), (Liu et al., 2017). This technique adaptively removes the reactive power sharing error with the help of an integral controller and attains the resistive value by keeping reactance-to-resistance (X/R) ratio constant. However, this topology requires physical parameters information. Further, it is complex in industrial applications which reduces the proficiency of the suggested technique.

For accurate power sharing, another technique based on the concept of anti-droop controller has been discussed (Gao et al., 2018). The implementation of this method requires communication signal and information of feeder line impedances which degrades the efficiency of the technique. Stochastically manage the reactive power another topology is planned which employs the injection of uncertain real power to acquire the real time monitoring method for reactive power sharing (Kekatos et al., 2015). However, this algorithm is complex and requires the low bandwidth communication signal. To overcome the issue of voltage and frequency deviations, a secondary voltage and frequency control loop technique has been demonstrated which requires the communication signals for accurate reactive power sharing (Lu et al., 2017). However, requirement of communication links enhances the cost of the network thus making it laborious. Another consensus based voltage control technique has been proposed for appropriate reactive power sharing with only need the distribution signal of communication among converters (Consensus-based, 2015). However, this algorithm is complex and facilitate only the average change of voltage, whereas the overall minimization of voltage fluctuations has not been measured. A new reactive power control technique based on consensus method has been presented to increase the flexibility of the network which do not require the information of feeder line impedances (Zhang et al., 2017), (Zhou et al., 2018). However, communication delay or failure minimizes the performance of the proposed topology.

An adaptive Q-E droop control technique is described to adequately reduce the reactive power sharing error by calculating the voltage drops and send it to the central controller (He, Li and Blaabjerg, 2015), (Mahmood, Member and Michaelson, 2014). The controller modified the droop curve according to the collected data. However, the use of central controller and communication link makes the technique complex and expensive. Furthermore, the coefficient of adaptive impedance is tough to be attain. For instance, in (Mahmood, Michaelson and Jiang, 2015) a technique based on the concept of adaptive virtual impedance and consensus control has been proposed. Although, this topology does not require the information of feeder line impedances, but it needs the sparse communication which decrease the reliability of the network. To resolve the issue of communication signal, a technique based on adaptive virtual impedance is suggested in (Hu et al., 2018). It enhances the accurate sharing of reactive power by setting the square of reactive power sharing ratio coefficient. However, this topology requires the information of feeder line impedances.

Another contribution to appropriately share the reactive power between DG units according to the variations in their operating point was proposed in (Han et al., 2014). This technique initiates the error elimination procedure which disturbs the voltage. The voltage is then recovered by voltage recovery operation. To mitigate the errors of reactive power sharing, another technique was described in (He and Li, 2011)-(He and Li, 2012). This technique has been employed in two different stages. In first stage, conventional droop control technique is deployed, and the coupled real and reactive powers are used for the calculation of reactive power sharing error at the second stage. Integration term is utilized to eliminate the errors. However, these topologies are activated by the low bandwidth synchronized communication signal which enhances the cost and decreases the reliability of the network.

To compensate the problem of communication links for accurate reactive power sharing, a modified technique has been presented which uses the infrequent measurement of point of common coupling voltage to compute the mismatches among output impedances (Issa et al., 2016). However, this topology is badly influence by resistive line impedances and the structure of microgrid network.

The load variation in different MG modes and operating points disturb the power quality. The power quality can be enhanced by properly selecting the control parameters of droop and PI controllers. Small signal model analysis of microgrids are generally used to obtain the relevant control parameters (Krismanto, Mithulananthan and Lee, 2015). However, it requires the enormous trial and error approach to find the best parameters due to serious constraints and nonlinearities (Sevlam and Kumar, 2017).

In this context, a technique is required which will resolve these issues and accurately share the reactive power among different DG units. The proposed topology injects the transient reactive power in the frequency droop characteristic which is helpful for the computation of reactive power sharing errors. The correction scheme has been activated locally by monitoring the notable DG switching, load variations and mode shifting of the microgrid network. Thus, the need of communication channel/ signal is not required. Lastly, the PSO is used to optimize the parameters of droop and PI controller of inner control loop.

The rest of research paper is organized as follows: Section II gives a brief description about the microgrid structure and control. The proposed methodology for localized reactive power correction scheme is illustrated in Section III. Optimization of control parameters based on PSO algorithm is described in Section IV. Simulation results and discussion is outlined in Section V following the conclusion.

MICROGRID STRUCTURE & CONTROL

System Structure

The system consists of four different types of DG units in which 3 are of equal ratings (6KVA) and one is of half rating (3KVA). General structure is illustrated in Fig. 1.

To verify the accuracy of the proposed technique, the different line impedances are added in the system. It is assumed that the loads are the linear. In which, two are common and two are local loads. Local loads are added with common loads to make the system asymmetrical. *LC* filter is connected between the feeder impedances and the insulated-gate bipolar transistor *(IGBT)* bridge output. The network parameters are tabulated in Table 1.

Theoretical Analysis of Power sharing

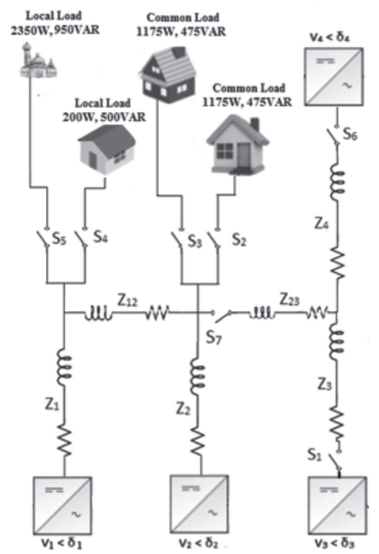


Fig. 1: Islanded microgrid structure

Table 1: Parameters of MG

Description	Parameter	Value
Nominal Voltage	VO	120V
DC offset Voltage	E	400V
Inverter Filter parameters	L_f, C_f	L=6 mH, C=40 µF
Sampling Period	T_s	5×10^{-6} sec
Feeder Impedances	Z	$Z_1=Z_2=Z_3=0.2+j_1.141\Omega$ $Z_{12}=Z_{23}=0.3+j0.754\Omega$

Distributed generators consist of different types of energy resources. Each of them is connected to the common AC bus through the power electronic interface. Impedances connected at the output of the inverter are pure inductive, θ = 90^o. Thus, the active and reactive powers drawn from the common AC bus is described as (M. Anwar, M. I. Marei, 2017):

$$P = \frac{E \times V_{com}}{X} Sin\theta \quad (1)$$

$$Q = \frac{E \times V_{com}}{X} Cos\theta - \frac{V_{Com}^2}{X} \quad (2)$$

where *P* and *Q* are the real and reactive powers respectively, θ is the angle among the common bus voltage and the inverter output voltage and *X* is the reactance of the inverter. *V* and *E* are the amplitudes of the load voltage and inverter output voltage respectively.

The conventional droop control method has been used for the equal sharing of active and reactive powers. This technique follows the principle of conventional synchronous generator and is divided into *Q-E* and *P-F* droop control techniques.

To design the reactive power droop control technique, it is necessary to set the acceptable range of voltage. As the load demand increases, the system needs more reactive power to compensate. Ultimately, the voltage of the system decreases (Hou *et al.*, 2018). The *Q-E* droop equation is written as (3).

$$E = E_O - K_{Qd.Q} \quad (3)$$

where *E, Q* and K_{Qd} demonstrates the voltage, reactive power and reactive power slope respectively. Further, it is required to fix the range of frequency in order to design the real power droop control technique. The network requires more real power to compensate if the load demand increases, resulting decrease in the frequency of the network. (Hou et al., 2018) The *P-F* droop equation is written as (4).

$$F = F_O - K_{Pd}.P \quad (4)$$

where *F, P* and K_{pd} demonstrates the frequency, real power and real power slope respectively. The values of K_{Qd} and K_{pd} are normally obtained from (5) and (6) respectively.

$$K_{Pd} = \frac{F_{Maximum} - F_{Minimum}}{P_{Maximum}} \quad (5)$$

$$K_{Qd} = \frac{E_{Maximum} - E_{Minimum}}{2Q_{Maximum}} \quad (6)$$

Droop control technique accurately share the active power across the DG units, while the reactive power has not been accurately shared because of its dependencies on the network configuration. The network configuration depends online impedances, filter characteristics and the selection of control parameters including droop coefficients (K_{Pd}, K_{Qd}) and *PI* controller (voltage & Current) of inner control loops, which needs to be adjusted properly for stable operation of the system.

Proposed Methodology

The primary concern of this work is to generate the communication free triggering signal for the initialization of synchronized reactive power correction scheme. The flow chart of the proposed synchronized reactive power correction scheme is shown in Fig. 2.

From Fig. 2 it is clear that the proposed topology has

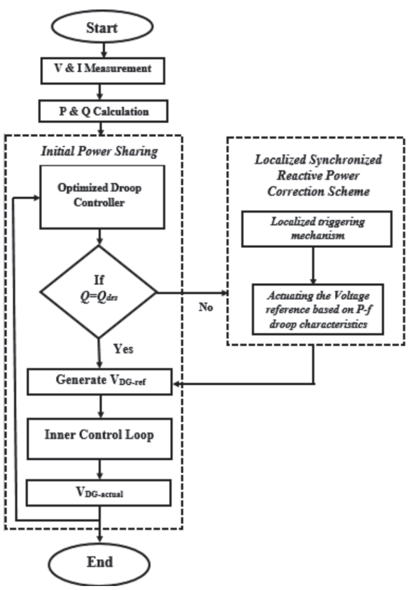


Fig. 2: Flow chart of localized synchronized reactive power correction scheme

two different stages and is explained as follows:

1. Initial power sharing by utilizing the optimized droop control technique
2. Localized synchronize reactive power correction scheme

Stage 1: Initial Power Sharing

The control parameters are disturbed when microgrid network is transferred from the grid mode to the islanded mode. The network performance against disturbances is also dependent on the selection of control parameters including droop coefficients (K_{Pd}, K_{Qd}) and the *PI* controller (voltage & Current) of inner control loops apart from other network features. The detailed procedure for the selection of control parameters is discussed in section 4.

The optimized control parameters-based droop controller is utilized for real and reactive power sharing. The average values of real and reactive powers are computed with the help of low pass filters *(LPF)*. The moving average filters are further connected to filter out the ripples. In this regard, the correct value of the desired real power (P_{des}) is computed which is utilized at stage 2 for determination of voltage reference. Further, the reactive power is also computed at this stage. If Q is equal to the desired reactive power (Q_{des}), then reference voltage (V_{DG-ref}) will be generated, otherwise stage 2 will be activated. This V_{DG-ref} is used by inner control loop to generate the DG actual voltage ($V_{DG-actual}$).

Stage 2: Localized synchronize reactive power correction scheme

This stage is implemented in two different steps i.e.; Localized Triggering mechanism and Actuating the Voltage reference based on *P-F* droop characteristics. These steps are briefly discussed as follows:

a) Localized triggering mechanism: The operating point of DG plays a vital role in appropriate sharing of active and reactive power. However, the operating point disturbs due to following conditions.

1. The powerful variations in the loads of the microgrid network.
2. The shutdown or start up procedures of the DG units in MG network.
3. The transition of microgrid network from grid connected to islanded mode and vice versa.

These deviations in operating point create changes in the reactive power sharing. This change in reactive power acts as a communication free triggering flag/signal, thus, used to initialize the synchronized reactive power correction scheme. Fig. 3 demonstrates the proposed local generating signal mechanism for executing the reactive power correction scheme. Firstly, a high pass filter is used to eliminate the DC offset from *Q*. The comparator block compares it with the Q_{des} and generates the absolute change in reactive power (ΔQ). The ΔQ consists of incremented and decremented values of reactive power, specified according to damping speed. The damping speed is low for load variations, medium for the DG unit switching, and high for MG mode change. The power fluctuation eliminator is used to eliminate fluctuations and uniform starting signal is generated by the peak detector block. The uniform starting signal is converted to fixed type of information signal with the help of data type conversion. The transport delay block gives delay in the information signal to end the optimized droop control procedure. This fixed delay is for all DG units according to the characteristics of the system. After this, the appropriate delay for the correction of slop and y-intercept is provided by the sum of tapped delay. The triggering signal ($S_{Trigger}$) is ready for the actuation of voltage reference.

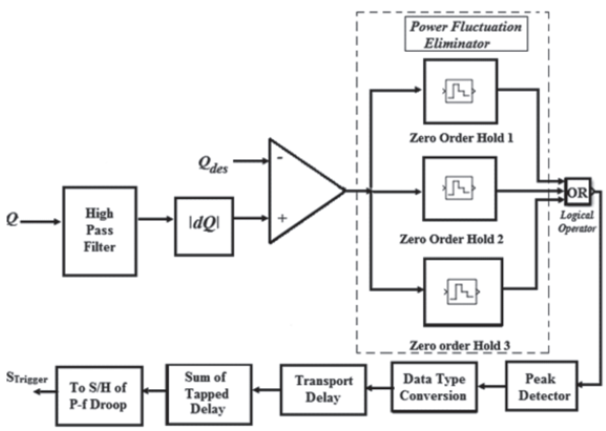


Fig. 3: Proposed localized triggering mechanism for reactive power correction scheme

Actuating the Voltage reference based on P-f droop characteristics: This stage is basically activated by the localized triggering mechanism. The $S_{Trigger}$ injects the reactive power transient in the frequency droop. As reactive power transient is coupled with the real power, this coupling disturbs the real power, ultimately, computes the reactive power sharing error. Once the correction strategy of the reactive power is triggered, Eq. (3) and (4) are replaced by the Eq. (7) and (8) respectively.

$$F = F_O - \left(K_{Pd}.P + K_{Qd}.Q\right) \quad (7)$$

$$E = E_O - K_{Qd}.Q + \left(\frac{I_C}{S}\right).\left(P - P_{des}\right) \quad (8)$$

where, I_C is Integral gain.

If Q is less than Q_{des} in one DG unit, the value of $(K_{Pd}P + K_{Qd}Q)$ will enhance. This increase will rise the value of frequency, ultimately, decreases the *P*. This variation in *P* disturbs the desired real power P_{des}, which is helpful in the correction of slop and y-intercept of the *Q-E* droop. The sample & hold block creates the difference between *P* and P_{des} which ultimately passed to the *PI* controller. The rate limiter generates the appropriate values of voltage and reactive power droop coefficient and respectively after the resolution of error in *PI* controller. The procedure is vice versa if reactive power (*Q*) is greater than desired reactive power (Q_{des}). The pictorial representation of this procedure is shown in Fig. 4.

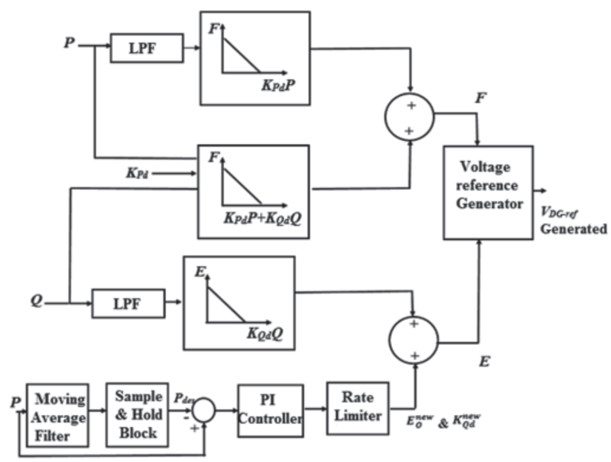


Fig. 4: Synchronized reactive power correction topology

These and generates *E* and *F* by using equations 7 and 8 respectively. Hence, each DG unit will attain the suitable operating point for the appropriate sharing of the reactive power. Upon successful completion of this scheme, $V_{DG\text{-}ref}$ is generated. This $V_{DG\text{-}ref}$ is utilized to generate the $V_{DG\text{-}actual}$ by inner control loop duly optimized by PSO.

Optimization of Control Parameters

The control parameters include droop coefficients

(K_{Pd}, K_{Qd}) and the *PI* controller (voltage & Current) of inner control loops. The decrement or increment of control parameters beyond the limits can lead the system towards instability. As the control parameters increase, rise time increases, overshoots in the system may enhance. Further, the settling time of the system also increases. These control parameters are selected by hit and trial method conventionally according to the upper and lower limits of voltage, frequency, real power and reactive power of the network. Further, it takes long estimation time to compute the best results. If the control parameters of *PI* controller and droop coefficients are selected carefully then the response of the system will be better. In this work, *PSO* technique is used for the selection of control parameters; droop coefficients (K_{Pd}, K_{Qd}) and the *PI* controller (voltage & Current) of inner control loops. The optimized control parameters which are used in reactive power correction scheme is depicted in Table 2.

Table 2: Optimized controller gains

Description	Parameter	Value
Droop Coefficient of Frequency	K_{Pd}	0.00124 Rad/(Sec.W)
Droop Coefficient of Voltage	K_{Qd}	0.00142 Rad/(Sec.W)
Current Controller Gain	K_I	KPV=0.23, KIV=0.001
Voltage Controller Gain	K_V	KPV=0.3, KIV=0.4

The system response with and without utilizing the optimized control parameters are shown in Fig. 5. The settling time and overshoot of the network using *PSO* is less than *17ms* and *28%* in comparison to non-utilization of *PSO*. Hence the system response is better upon utilization of *PSO* in comparison to conventional tuning method.

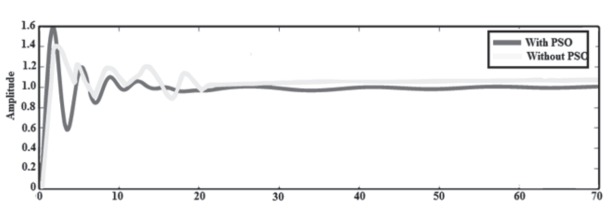


Fig. 5: Step response of network by utilizing PSO and conventional tuning method

RESULTS & DISCUSSIONS

An islanded microgrid system is simulated in MATLAB /Simulink to analyze the proficiency of the proposed methodology as compared to the communication-based topology. Control parameters droop controller coefficients (K_{Pd}, K_{Qd}) and PI controller (voltage and current Controller) of inner control loops were chosen from PSO. Following cases are analyzed to validate the proficiency of proposed technique at steady state condition.

Reactive Power sharing

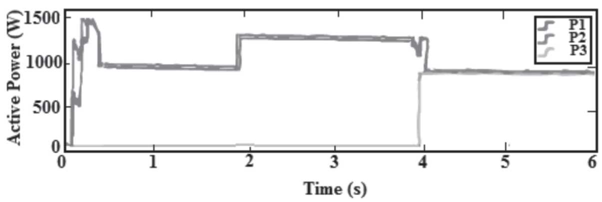
This case demonstrates the efficiency of the proposed method regarding enhancement of reactive power sharing. The results are compared with the traditional droop control and communication-based methods to further enlighten the efficiency. The network is suddenly switched to islanded mode, wherein two DG units of equal ratings (6KVA) are operational. One common load and one local load is connected to the network. At t = 2 sec, the load is increased greater than the capacity of these two DG units. At t = 4 sec, third DG is inserted in the network. These changes disturb the power sharing. The switching sequence for this case is illustrated in Table 3.

Table 3: Switching sequences of proposed topology

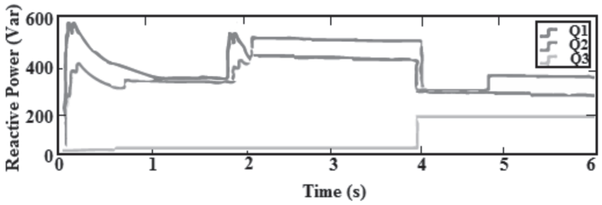
Period	Switches						
	S1	S2	S3	S4	S5	S6	S7
$0 \leq t < 2$	OFF	ON	OFF	ON	OFF	OFF	ON
$2 \leq t < 4$	OFF	ON	ON	ON	OFF	OFF	ON
$4 \leq t < 6$	ON	ON	ON	ON	OFF	OFF	ON

In conventional droop technique, the active power has been accurately shared. However, the reactive power has not been shared properly among 3 DG units due to operating point variations at t = 0, 2 and 4 seconds because of changes in mode, load and DG switching as shown in Fig. 6.

These issues were resolved by communication based synchronized reactive power correction scheme. In this scheme, disturb reactive power is injected in *P-F* droop



(a) Real Power



(b) Reactive Power

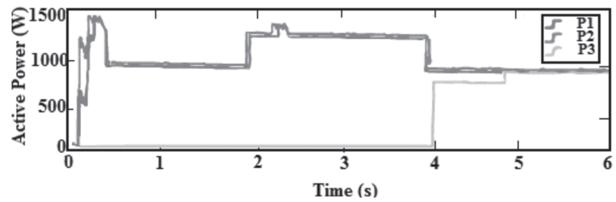
Fig. 6: Sharing under conventional droop technique

characteristic. This injection disrupts the actual value of real power sharing which is useful for the calculation of reactive power sharing error. However, there exists delay in communication signal for third DG Consequently, the reactive power has not been shared properly among 3 DG units as depicted in Fig. 7. The problem of communication delays is resolved by the proposed reactive power correction scheme. The scheme properly started at t= 0.7, 2.3 and 4.2 sec. The proposed scheme accurately shares the real and reactive power among 3 DG units as shown in Fig. 8. The injection of transient reactive power disturbs the real power for the activation of synchronized reactive power correction scheme. In conventional methods, the restoration of real power takes time. In comparison to it, the proposed topology restores the real power value in just *0.5* sec as shown in Fig. 7 and Fig. 8. Further, the control signals related to different steps of the localized triggering mechanism are depicted in Figs. 9 - 15.

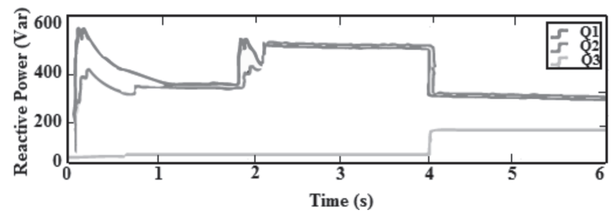
Local loads variations

The variation in local loads make the system asymmetrical, thus, disturbs the sharing of power across DG units. The local load is increased and decreased at *t* = 2sec and 4sec respectively. Switching sequence of case study 3 is illustrated in Table 4.

The reactive power correction strategy activated accurately. The reactive and real power has been properly shared between 3 DG units as displayed in Fig. 16.

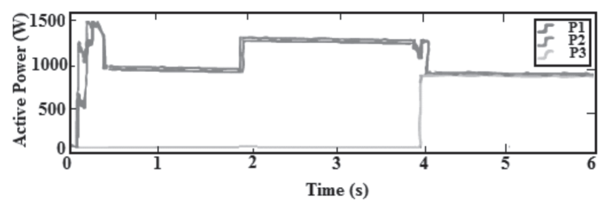


(a) Real Power

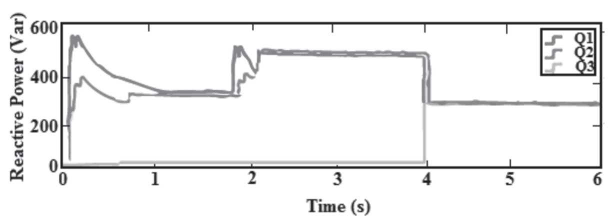


(b) Reactive Power

Fig. 7: Sharing under communication-based correction scheme



(a) Real Power



(b) Reactive Power

Fig. 8: Sharing under proposed localized synchronize reactive power correction scheme

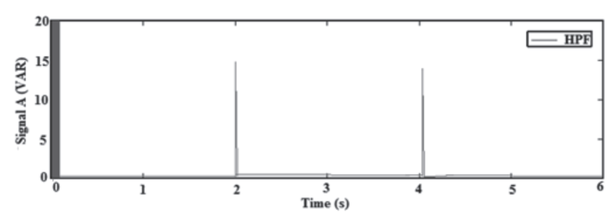


Fig. 9: Signal A (Overshoots in system reactive power due to variations in DGs operating point)

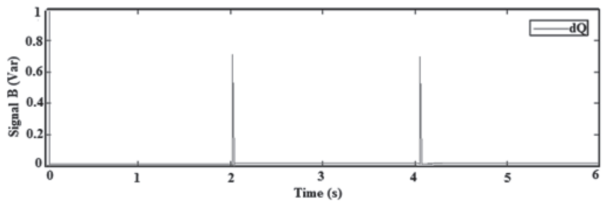


Fig. 10: Signal B (Comparison of Q and Qdes values)

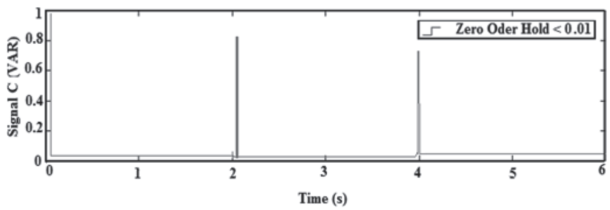


Fig. 11: Signal C (Small sampling period for removal of fluctuations of load change)

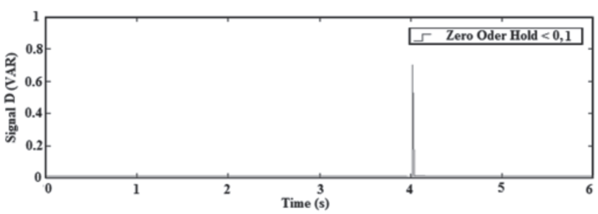


Fig. 12: Signal D (Average sampling period for removal of fluctuations of MG DG switching)

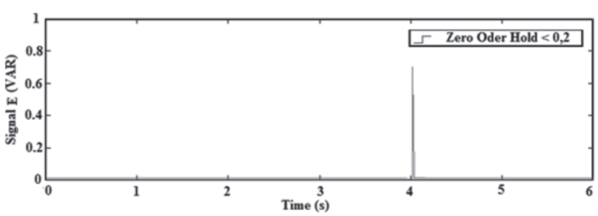


Fig. 13: Signal E (Large sampling period for removal of fluctuations of MG Mode change)

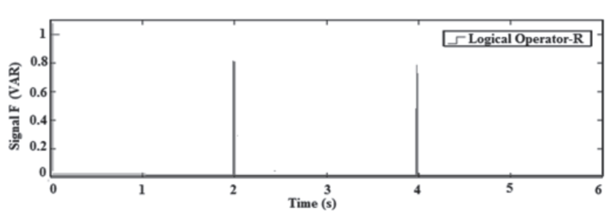


Fig. 14: Signal F(Combination of signals C, D & E)

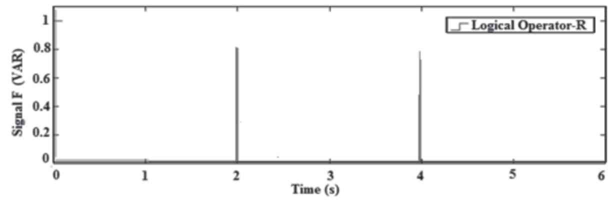
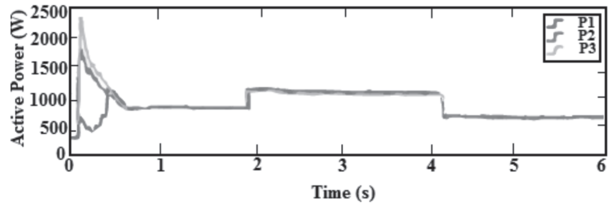
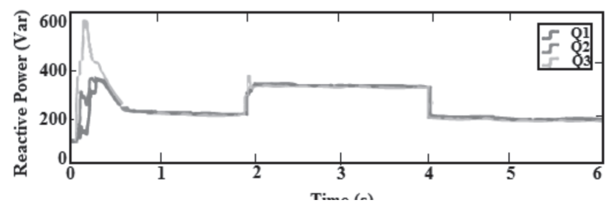


Fig. 15: Signal G (Uniform triggering signal)



(a) Real Power



(b) Reactive Power

Fig. 16: Sharing under local load variations

Table 4: Switching sequence in case of load variations

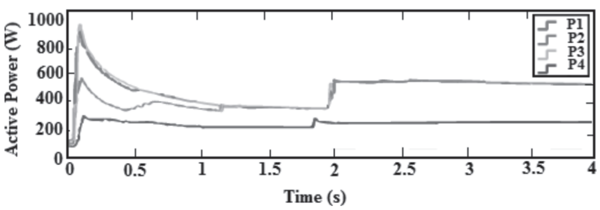
Period	Switches						
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
$0 \leq t < 2$	ON	ON	OFF	OFF	ON	OFF	ON
$2 \leq t < 4$	ON	ON	OFF	ON	ON	OFF	ON
$4 \leq t < 6$	ON	ON	OFF	ON	OFF	OFF	ON

Impact of Different DG ratings

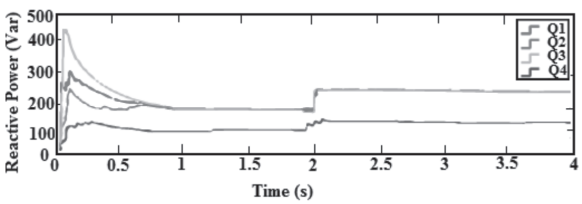
The proficiency of the proposed technique is also considered at different DG ratings. The four different rating DGs are switched in the system as per the requirement of load. In this work, the 3 DGs are continuously supplying power to the system. However, when the load is switched at $t = 2$ *sec*, the fourth DG is switched on. The proposed techniques detect this scenario appropriately and shared the real and reactive powers in a timely manner as shown in Fig. 17. The DG switching sequence is tabulated in Table 5.

Table 5: Switching sequence in case of different DG ratings

Period	Switches						
	S1	S2	S3	S4	S5	S6	S7
$0 \leq t < 2$	ON	ON	OFF	OFF	ON	ON	ON
$2 \leq t < 4$	ON	ON	ON	OFF	ON	ON	ON



(a) Real Power



(b) Reactive Power

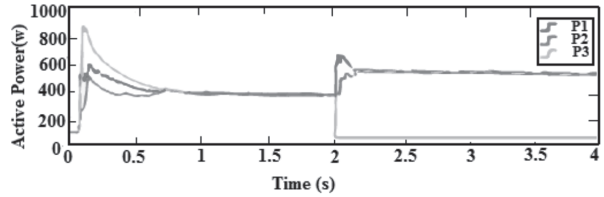
Fig. 17. Sharing under different DG ratings

Table 6: Switching sequence in case of different DG ratings

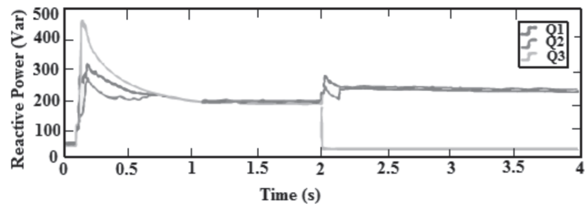
Period	Switches						
	S1	S2	S3	S4	S5	S6	S7
$0 \leq t < 2$	ON	OFF	ON	OFF	ON	OFF	ON
$2 \leq t < 4$	OFF	OFF	ON	OFF	ON	OFF	ON

Feeder faults influence

When faults occur in the MG, the network alters, thus disturbs the internal circuit structure and disturbs the network dynamic relationships. The proposed technique is considered to analyze these faults. Before the occurrence of faults, the 3 DGs are in the system. At t= 2 sec, faults are occurred at DG_3. The associated circuit breaker *(C.B.)* trips the DG_3. The proposed technique detects this situation and appropriately shares the active and reactive powers among the two DG units. The switching sequence for this scenario is given in Table 6. Figs. 18 – 20 shows the response of proposed topology for single, two and three phase to ground faults.

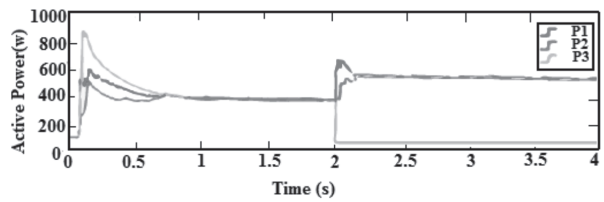


(a) Real Power

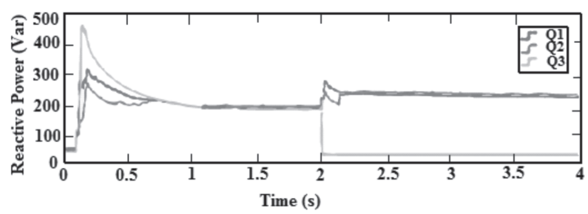


(b) Reactive Power

Fig. 18. Sharing in single phase fault

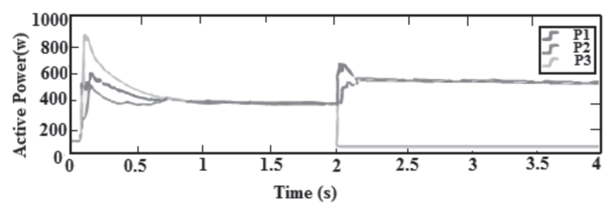


(a) Real Power

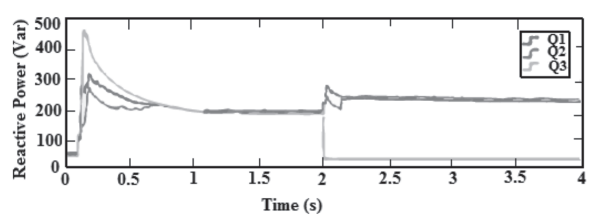


(b) Reactive Power

Fig. 19. Sharing in double phase to Ground Faults



(a) Real Power



(b) Reactive Power

Fig. 20. Sharing in three phase faults

Influence of Different X/R ratios

Reactive Power sharing is sensitive to the *X/R* ratio. The conventional droop control technique was established assuming highly inductive line impedances. However, this supposition is challenging in LV MG networks where distribution lines are mainly resistive or complex (Han *et al.*, 2016). This is a major hurdle in the accurate sharing of reactive power among different types of DG units. This case tests the accuracy of the proposed methodology performance against the two different values of *X/R* ratio of low and medium voltage MG. Eq. (9) & (10) are utilized to compute the real and reactive power sharing errors against the two different *X/R* ratios (Golsorkhi *et al.*, 2014). The two different values considered for the *X/R* ratio are 0.3 and 0.8 respectively.

$$\Delta P_{error,max} = max\left\{\frac{P_O}{P_{P,act}} - \frac{\sum_{i=1}^{4} P_O}{\sum_{i=1} P, actu}\right\} \quad (9)$$

$$\Delta Q_{error,max} = max\left\{\frac{Q_O}{Q_{Q,act}} - \frac{\sum_{i=1}^{4} Q_O}{\sum_{i=1} Q, actu}\right\} \quad (10)$$

Where and denotes the active and reactive power sharing error respectively. P_O, P_{act}, Q_O and Q_{act} show the real power, desired real power, reactive power and desire reactive power respectively. Table 7 shows the error sharing in active and reactive power at different values of *X/R* ratio. The comparison with conventional droop control further highlights the significance of proposed technique.

These case studies show the efficiency of the proposed technique. Furthermore, the significant features of the proposed technique are compared with the techniques of recent published work in order to further highlight the prominent features as tabulated in Table 8.

Table 7: Power sharing error at different X/R ratio

Details	Starting Load				Increased Load			
	Conventional droop Controller		Proposed Controller		Conventional droop Controller		Proposed Controller	
X/R ratio	1.8	0.3	1.8	0.3	1.8	0.3	1.8	0.3
Max P sharing error	1.3%	34.81%	0.12%	0.2%	0.17%	7.69%	0.13%	0.03%
Max Q sharing error	74.75%	0.18%	0.22%	0.08%	12.53%	0.13%	0.06%	0.12%

Table 8: Comparison of recent published work with proposed technique

Recent published work	Proposed Technique
(Dou et al., 2017),(Hu et al., 2018),(Liu et al., 2017) require information of physical parameters of microgrid network for accurate sharing of reactive power. Thus, these techniques are laborious.	In it, the synchronized reactive power correction scheme has implemented the phenomena of coupled active and reactive power. Hence, it is not influenced by the physical parameters of MG network.
Conventional techniques need communication signal for the activation of reactive power correction scheme, which decreases the reliability of the network (Gao et al., 2018),(Lu et al., 2017).	In this technique, the variations in DGs operating point is considered as the communication free starting flag for the activation of reactive power correction scheme. It enhances the reliability of the system by abolishing the role of communication signals.
The requirement of communication signal for the activation of reactive power correction topology makes the correction process sluggish and inaccurate (Zhang et al., 2017),(Zhou et al., 2018).	Localized reactive power correction scheme in the proposed work triggers without communication signal, making the correction process fast and preserves the plug and play attributes of the DG units.
In conventional techniques, the parameters of droop and PI controller of inner control loop are selected by a hit and trial method. This affects the precision and accuracy. Further, it takes long estimation time to compute the best results (Kayalvizhi and Vinod Kumar, 2017).	In this work, the parameters of droop and PI controller of inner control loop are obtained by utilizing the particle swarm optimization technique.

CONCLUSION

In this paper a localized signal generating mechanism has been presented for the accurate sharing of reactive power. Operating point variations in *DG* unit due to load, mode and DG switching variations in a *MG* network is considered as a communication free starting flag. The flag activates the synchronized reactive power correction scheme. Further, *PI* controller is used for the correction of slop and y-intercept of *Q-E* droop curve. Moreover, *PSO* technique is adopted for the careful selection of system control parameters (Voltage, Current and droop controller). This technique obviates the requirement of central controller and communication signal between DGs. From the proposed topology, real and reactive powers have been properly shared among DGs and the network becomes more stable and reliable as compare to the communication-based topologies.

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