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ERIGrid TRANSNATIONAL ACCESS PROJECT REPORT

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PROJECT Details

User Project Acronym	REPRMs (No: 01.006-2016)
User Project Title	**Reliability Enhancement in PV Rich Microgrids with Plug-in-Hybrid Electric Vehicles and Data Centres**
Main scientific/technical field	**Energy, Environment**
Keywords	Power distribution systems, Smart electric grid, Microgrid with PHEVs & DCs, Solar Photovoltaic Systems, Optimization algorithms

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Abstract and Objectives

Microgrid is a small scale power supply network that is designed to provide power for a small community or power systems with limited electrical boundaries. The microgrids can operate in grid connected mode as well as in isolated/off grid mode. Microgrids with high penetration of renewable energy sources, like photovoltaic (PV) generators, is inevitable. Battery, one of the power sources of an plug-in hybrid electric vehicle (PHEV), can be used as load or Distributed Generator (DG) according to the operating conditions and is known as *vehicle-to-grid* or V2G concept. The same principle can also be extended to Data Centres (DC) as they have battery storage systems. In this connection, this project proposes to achieve the following objectives.

1.   To study the reliability of existing microgrid systems with PV generators, PHEVs and DCs

2. To enhance the reliability of microgrid through optimal integration of (DGs)

3. To develop a methodology to emphasize the contribution of PHEVs and DCs in improving the reliability of microgrids with high PV penetration.

The efforts outlined in this proposal will directly impact the national needs for analyzing the power distribution system by forming microgrids. Further, the research will provide a way for measurable and tangible improvements in reliability with microgrids that can accommodate DGs are of national and international interest.

STATE-OF-THE-ART

Europian Union Energy Policy [1 and 2] and the Indian National Electricity Policy of 2005 [3 and 4] have emphasized the need of strengthening the regional power grids, power transmission and distribution networks, and the need to develop an emergency response system for power safety and reliability, and the necessity to reinforce the priority policies for generation of electrical energy from renewable sources.

There are concentrated efforts in research, development, and demonstration (RD&D) currently in progress in Europe, the United States, Japan, Canada and in India on microgrids which are capable of providing quality power with imporoved reliability when compared with state-of-art power distribution systems.

In this connection, there is a need to study and understand the reliability of the existing power distribution systems, thereby, identification of potential threats which can affect the operation of the existing power grid systems. As the penetratin of PV based microgrid systems are increasing at fast rate, in the recent past, few researches have proposed the reliability studies of microgrid. Storage-reserve sizing problem with qualified reliability is raised to integrate reserve sizing and loss-of-load probability (LOLP) index into existing storage sizing problem is analysed in [5]. In [6], the methodology for optimizing investment in DC's battery storage capacity is discussed. A model for calculating the optimal size of an energy storage system (ESS) in a microgrid considering reliability criterion is proposed in [7]. In [8], the effects of the protection system on the reliability of a microgrid integrated with weather-dependent micro-sources is investigated.

However, the existing reliability indices and standards need to revisited to quantify the reliability of future microgrids with the integrtation of variable or non-dispatchable power sources, like PVs, PHEVs and DCs.

Therefore, for the first time, this project proposes to study and formulate the methodologies to enhance the reliability to keep abreast to the upcoming renewable rich microgrids, hence the future smart grid technologies and its advancements.

Reliability Enhancement in Microgrid

Distribution system is inherently dynamic, with variance in sources and loads. Need to seek out how to manage this time-bearing phenomenon. Further, these solutions can be tested by forming a microgrid. The battery of PHEVs and the battery banks of DCs can be used as loads or DGs.

To study the reliability of microgrid, indices like Energy Reliability Index (ERI), Loss of Load Index

(LOLE), Average System Availability Index (ASAI), Customer average interruption duration index (CAIDI), System average interruption frequency index(SAIFI), Average customer curtailment index (ACCI), Unavailability, Percentage reserve margins(PRM), Failure rate, Forced outage rate(FOR) and Power Not Supplied index(PNSI) are to be observed and analyzed [9]. However, among these indices the ERI is critical parameter which principally decides the other indices or can be calculated subsequently. Moreover, directly quantifies the reliability of the microgrid energy availability in the period of study. It can be calculated as

$$ERI = 1 - \frac{Expected\ energy\quad demand\quad not\quad served}{Total\quad energy\quad demand}$$

The ERI is calculated for the considered system prior and after the integration of PV, PHEV and DC.

While improving the reliability of microgrid with integrated PVs, the profits to customers who own PHEVs, data centres are to be maximized with the help suitable meta-heuristic optimization algorithms like genetic algorithm (GA) and particle swarm optimization (PSO). However, given its advantages, bat algorithm (BA) [10] is employed in this study for devising the optimization schedules with improved reliability for renewable rich microgrid. A brif description of the BA is given below.

The BA is a real coded population based meta-heuristic optimization method that mimics a group of Bats searching for the location of maximum availability of prey. The feasible solutions are the echolocations of micro bats. Based on Frequency-tuning technique to control the dynamic behavior of a swarm of bats i.e. evolution of group of bats carried by the individual performance and a global exchange of group. In the BA, a set of Bats with different adaptabilities but same structures are considered as population. A virtual bat at a position (X_i) flies randomly with a velocity (V_i) with variable frequency or wavelength and loudness (A). By changing frequency, loudness (A) and pulse emission rate (r) bat searches and finds its prey.

With the help of BA, without sacrificing the aforesaid objectives, the cost of operation and system loss of microgrid have to be minimized.

Optimal operation of the PHEVs, data centres and other DGs, while exploring the capabilities and with due consideration to respective limitations of different devices, is proposed to achieve for the considered microgrid system while ensuring improved reliability.

As a whole, this project execution involves the following steps:

   a) Modelling, integration of DGs thereby realization of microgrid

   b) Develop/define reliability metrics/indices

   c) Reliability assessment in microgrid

   d) Finding optimal dispatch of DGs, PHEVs and DCS with the help of BA while minimizing the loss, and cost with improved reliability

   e) Experimental validation of dispatch schedule and their actual applicability in the system considered

Modelling, integration of DGs thereby realization of microgrid

European medium voltage distribution network benchmark model as shown in Fig. 1 is considered for study in this project. The line parameters of the considered benchmark system are given in Table1 whereas the load data is given in Table2. For the simulation studies, the system is developed in Matlab-Simulink platform. However, given the limitations in the experimentation resulting from the DG ratings, the considered system has been adapted to 208V.
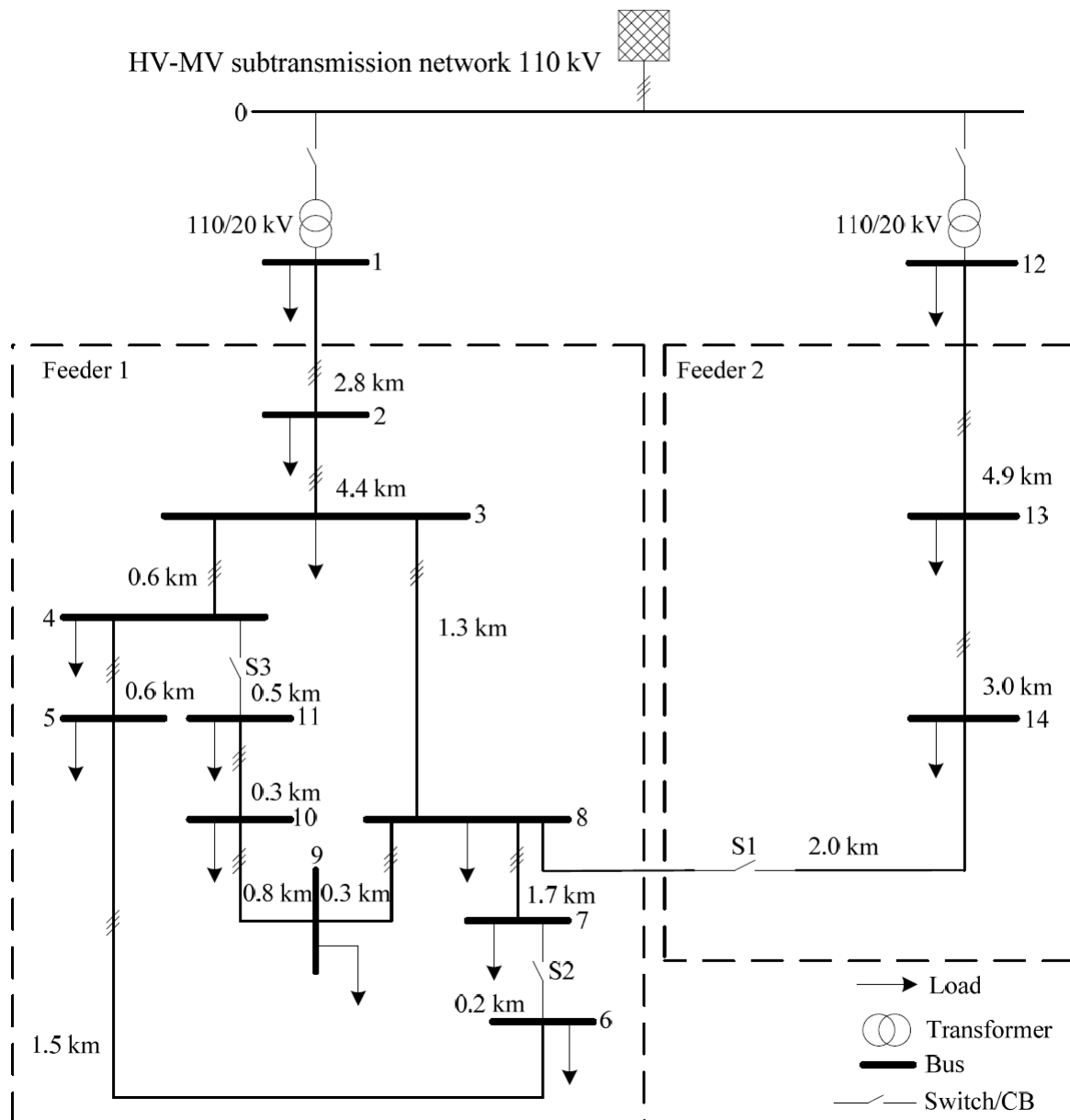

Fig. 1 Topology of European MV distribution network benchmark [11]

Table1 : Line data of the considered benchmark system [11]

Line segment	Node from	Node to	Conductor ID	R'_{ph} [Ω/km]	X'_{ph} [Ω/km]	B'_{ph} [μS/km]	R'_0 [Ω/km]	X'_0 [Ω/km]	B'_0 [μS/km]	l [km]	Installation
1	1	2	2	0.501	0.716	47.493	0.817	1.598	47.493	2.82	underground
2	2	3	2	0.501	0.716	47.493	0.817	1.598	47.493	4.42	underground
3	3	4	2	0.501	0.716	47.493	0.817	1.598	47.493	0.61	underground
4	4	5	2	0.501	0.716	47.493	0.817	1.598	47.493	0.56	underground
5	5	6	2	0.501	0.716	47.493	0.817	1.598	47.493	1.54	underground
6	6	7	2	0.501	0.716	47.493	0.817	1.598	47.493	0.24	underground
7	7	8	2	0.501	0.716	47.493	0.817	1.598	47.493	1.67	underground
8	8	9	2	0.501	0.716	47.493	0.817	1.598	47.493	0.32	underground
9	9	10	2	0.501	0.716	47.493	0.817	1.598	47.493	0.77	underground
10	10	11	2	0.501	0.716	47.493	0.817	1.598	47.493	0.33	underground
11	11	4	2	0.501	0.716	47.493	0.817	1.598	47.493	0.49	underground
12	3	8	2	0.501	0.716	47.493	0.817	1.598	47.493	1.30	underground
13	12	13	1	0.510	0.366	3.172	0.658	1.611	1.280	4.89	overhead
14	13	14	1	0.510	0.366	3.172	0.658	1.611	1.280	2.99	overhead
15	14	8	1	0.510	0.366	3.172	0.658	1.611	1.280	2.00	overhead

Table2 : Load data of the considered benchmark system [11]

Node	Apparent Power, S [kVA]		Power Factor, pf	
	Residential	Commercial / Industrial	Residential	Commercial / Industrial
1	15300	5100	0.98	0.95
2	---	---	---	---
3	285	265	0.97	0.85
4	445	---	0.97	---
5	750	---	0.97	---
6	565	---	0.97	---
7	---	90	---	0.85
8	605	---	0.97	---
9	---	675	---	0.85
10	490	80	0.97	0.85
11	340	---	0.97	---
12	15300	5280	0.98	0.95
13	---	40	---	0.85
14	215	390	0.97	0.85

Develop/define reliability metrics/indices

As aforementioned, the Energy Reliability Index (ERI) is the critical parameter in assessing the reliability of the microgrid system. Hence, the ERI is considered for improvement in this project. Accordingly, ERI is defined as

$$ERI = 1 - \frac{Expected\ energy\quad demand\quad not\quad served}{Total\quad energy\quad demand}$$

However, to calculate ERI one should have the information of outage rate. Outage rates are considered as follows.

The outage rates (λ) (Faults/year) are varying from 1.562 to 2.629 for various equipment of the distribution system. In this study the grid outage rate is considered as 2. The fault clearing time (r) is taken as 20hours. Total unavailability (U) of the grid for reliability analysis is 2*20 = 40 hr/year and Forced outage rate (FOR) is calculated as U/8760.

The following table presents the FOR of various generators.

Table3: FOR of different DGs

	FOR
Conventional Generation	0.015
DG1	0.002
DG2	0.003

Reliability assessment in microgrid

The reliability index ERI is '1' for ideal distribution system, where no failure/faults occur in any equipment/generation.

For the considered CIGRE distribution system, if no DG is added to the system, the ERI can be calculated as ERI=1-(44.39*0.015/44.39)= 0.985.

Total system load is 44.39kW, 0.015 is FOR of Conventional Generation (grid).

Finding optimal dispatch of DGs, PHEVs and DCS with the help of BA while minimizing the loss, and cost with improved reliability

The objective of this Project is to improve the reliability by placing DGs with appropriate size at optimal location. The Multiple objectives considered in this study are System loss, operating cost of DGs, voltage deviations and ERI. Multi objective optimization is formed by combining all the objectives with appropriate weights. For normalization, indices of the objectives are considered instead of original objectives directly.

The multi objective function is defined as

$$OF = \left(W_1 * ILP + W_2 * ILQ + W_3 * iCost + W_4 * IVD \right)$$

where, ILP is active Power loss index, it is defined as ILP= TPLWDG/TPLWODG, TPLWDG is total power loss with addition of DG, TPLWODG is total power loss without addition of DG.

ILQ is reactive Power loss index, it is defined as ILQ= TQLWDG/TQLWODG, TQLWDG is total reactive power loss with addition of DG, TQLWODG is total reactive power loss without addition of DG.

The cost related index 'icost' is the ratio of cost of operational DGs upon maximum operational cost of all DGs. IVD is the voltage deviation index.

The objective function is to be minimized with equality and inequality constraints and maintained minimum reliability.

Equality constraints

$$Pgs + \sum_{DER=1}^{m} P_{DER} = P_{load} + P_{loss}$$

Inequality constraints

$$V_{i\,min} \leq V_i \leq V_{i\,max}$$

The weights are indicated to give the corresponding importance to each impact indices for the penetration of DGs and depend on the required analysis.

In this Project, a metaheuristic optimization algorithm, the BA is used. It contains 60 bats. Each Bat is represented with the placement and Size of DGs. Maximum number of iterations is limited to 500. In this study, the rate is taken as 0.4 for first population and it is gradually increased with the number of iterations. The loudness value is taken as 0.7. For PV DG maximum rating is fixed to 10kW and 5KVAr and the PHEV/DC rating is fixed at 6kW and 3KVAr.

System is not having global solution because of limited DG rating. With better exploitation and exploration Bat performs giving better local minima. The complete algorithm is shown with flow chart as given in Fig. 2.

Read System parameters, Minimum and maximum size of DGs

Read Nbat, bfmin, bfmax, itermax, A, r

Generate initial population of bats within limits.

Run loadflow according to the bats. And calculate ploss, max cost and ERI

Calculate the fitness of all bats, find the best bat and corresponding fitbest.

Iter =1

i=1

Solution update
bf(i)=bfmin+(bfmax-bfmin)*rand
vel(i)=vel(i)+(sol(i)-best)*bf(i)
Solnew=sol(i)+vel(i)

If (rand>r) → YES → Solnew=best+0.01*randn

NO

Run Load flow according to Solnew and calculate Objective functions

Calculate the corresponding fitnessnew

Sol(i)=Solnew
Fitness(i)=fitnessnew ← YES — If (fitnessnew>fitness(i) && rand<A)

NO

If fitnessnew>fitbest → YES → Best=solnew
Fitbest=fitnessnew

NO

If (i=nbat) → NO → i = i+1

iter = iter + 1 ← NO — If(iter=itermax)

Obtain Gbest
Obtain the DG best location and size,
& DG Operating Cost, Loss and Best ERI.

Print the results

Fig.2: Flow chart of Bat algorithm

Table4 : Optimal Locations and Schedules of DGs

Distribution generations type	Optimal DG BUS Number	DG Value Active power(kW)/ reactive power (kVAr)	Active power loss (kW)	Reactive power loss (kVAr)	EIR
No DG Added (Base Case)			0.956kW	0.00433kVAr	0.9850
DG1-PV	9	10kW / 5KVAr	0.468kW	0.00211kVAr	0.9879
2DGs (1PV, 1 PHEV)	9	10kW, 5KVAr	0.188kW	0.000833kVAr	0.9906
	5	6kW, 3KVAr			
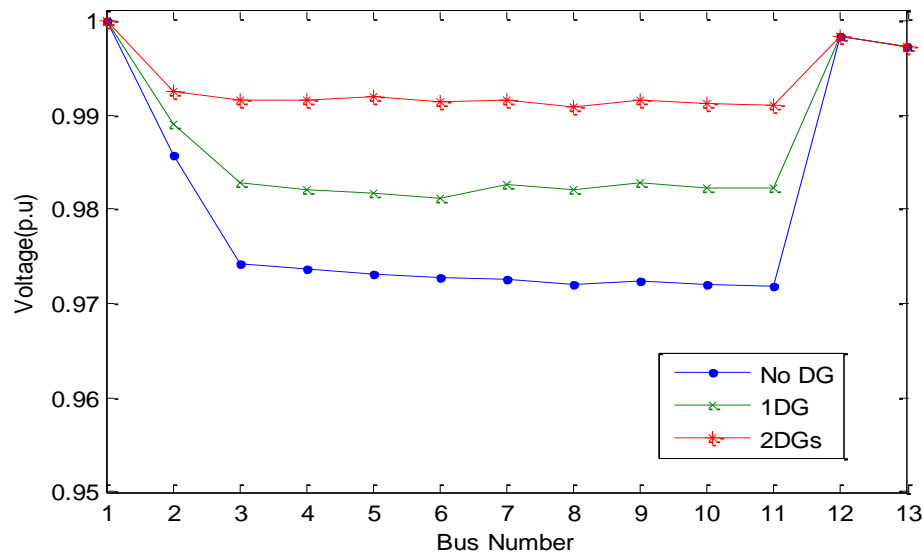
Fig.3: Voltage profile with and without DGs

Reliability assessment in microgrid with optimal DGs

For the considered CIGRE distribution system, if no DG is added to the system, the ERI can be calculated as ERI=1-(44.39*0.015/44.39)= 0.985.

Total system load is 44.39kW, 0.015 is FOR for Conventional Generation (grid).

With Addition of 1DG with 10kW
ERI=1-((34.39*0.015)+(10*0.002)/44.39)=0.9879

With addition of 2DGs
ERI=1-((24.39*0.015)+(10*0.002)+(6*0.003)/44.39)=0.991

Experimental validation of dispatch schedule and their actual applicability in the system considered

An experimental set-up has been made to validate the proposed solution which resulted in optimal schedules as calculated in aforementioned sections, for the improvement of reliability in the considered European MV distribution system as shown in Fig.1.

The considered distribution system which is operating as microgrid in this study is modelled in Matlab-Simulink environment. The same system is synthesized in Opal-RT system shown in Fig. 4.
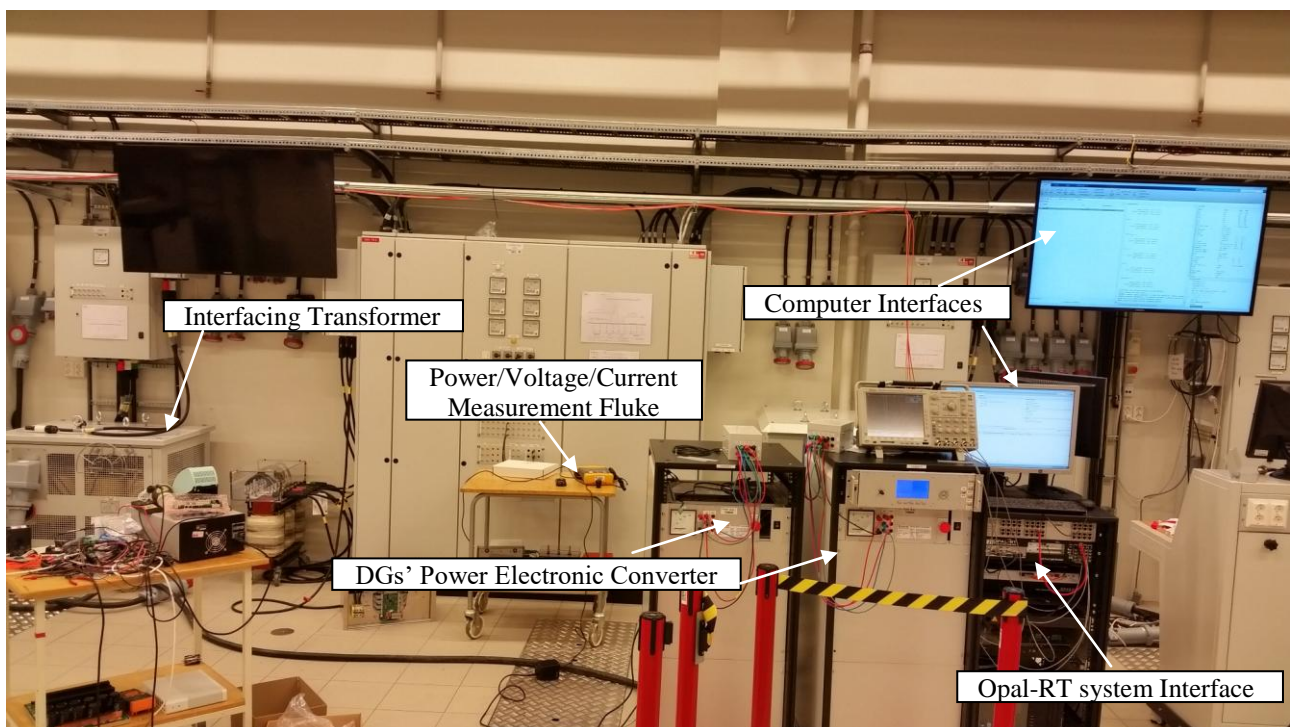
Fig. 4 Experimental Set-up Part-1

As it is concluded in the preceding section, the PV generator is decided to connect at bus number 9. Since the developed microgrid system is a virtual power system and is running in real time in Opal-RT system, all the three phase terminals of bus number 9 have been brought out for physical access. However, the terminals brought out from Opal-RT system are virtual terminals representing the original terminals. These terminals which are brought out for access are operating at low voltage (20V maximum) and cannot handle currents more than few milli amperes.

On contrary, the DGs which are expected to connect to the virtual power system running in Opal-RT are real converters which are running at actual system voltage of 208V and are expected to deliver powers in the range of KW and KVAr. Hence, a grid emulator, as shown in Fig. 5, is employed to interface the actual DGs with the virtual bus from the Opal-RT.

Fig. 5 Experimental Set-up Part-2 (Grid Emulator)

The two level power electronic converter supplied from DC bus bar is controlled deliver the required real and reactive power, hence acting as DG. The output of the converter is feeding the grid emulator which is in-turn interfaced with the virtual power system through the bus terminals brought from Opal-RT system. Since the DG/converter, hence the grid emulator has to generate the voltage and currents thereby the powers in synchronism with the bus number 9, the voltages are measured at bus number 9 and are used to generate the sinusoidal templates for converter outputs.

To maintain the voltage of the DC bus that is feeding the converter DGs, another power electronic converter is employed and is operated in rectifier mode.

Due to the limitation in number of DGs that can interfaced with the grid emulator (6 output terminals), which is in-turn used to interface with the microgrid in Opal-RT system, the maximum number of DGs that can be interfaced are limited to two. Hence, in the later part of the experiment, two DGs are interfaced at bus number 9 and at bus number 5. The converter DG at bus number 9 is considered as PV generator while the DG interfaced at Bus number 5 is considered as PHEV/DC.

Experiments Conducted and Results Analysis:

To validate the proposed project and the conclusions derived from the simulations, three experiments are conducted, as, 1. Microgrid system with Single DG (PV), 2. Microgrid system with two DGs, (PV and PHEV/DC).

Experiment-1: Microgrid system with Single DG-PV generator

As aforementioned, the PV DG is connected at bus number 9 which is the optimal location for single DG integration to the considered microgrid system. As it is inferred in optimal scheduling section, this DG is controlled to deliver 10KW at 0.9 pf lead, i.e. supplying 5KVAr to the system.

This experiment is formulated to quantify and validate scheduled power flows and their practical feasibility to improve the reliability of the existing microgrid system. In this experiment the loads at buses 5, 6 and 11 are increased by 30%, one at a time, respectively at every 3s. The load at bus number 11 is decreased by the same amount (30%) at 12s. The following Fig. 6 shows the rms line voltage at bus number 11, least voltage bus without addition of any DGs with adopted base loads. It can be seen that the initial voltage is 192.3V and is decreasing at 3s, 6s, and 9s in steps and is increasing at 12s, since for the first three instants the load is increasing while at the fourth instant, that is at 12s the load is decreasing.
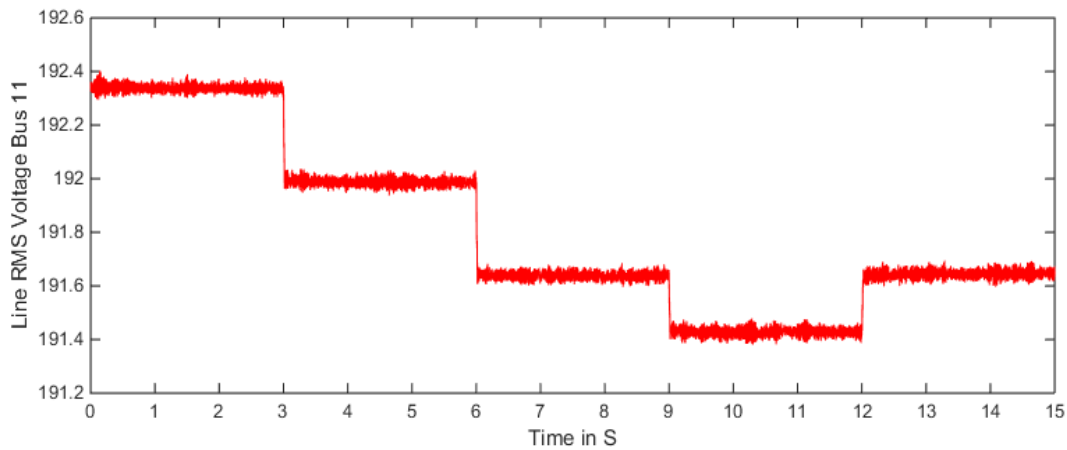
Fig. 6 RMS Line Voltage at bus number 11

The instantaneous voltage at bus number 9 at which the PV DG is connected is shown in Fig. 7 and its zoomed version is shown in Fig. 8
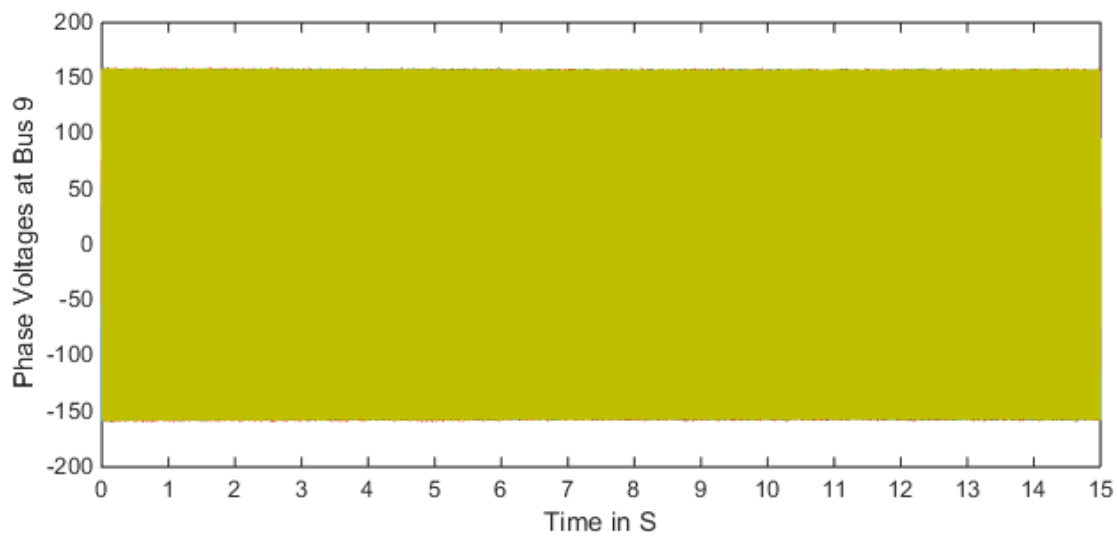
Fig. 7 Instantaneous phase voltages at bus number 9
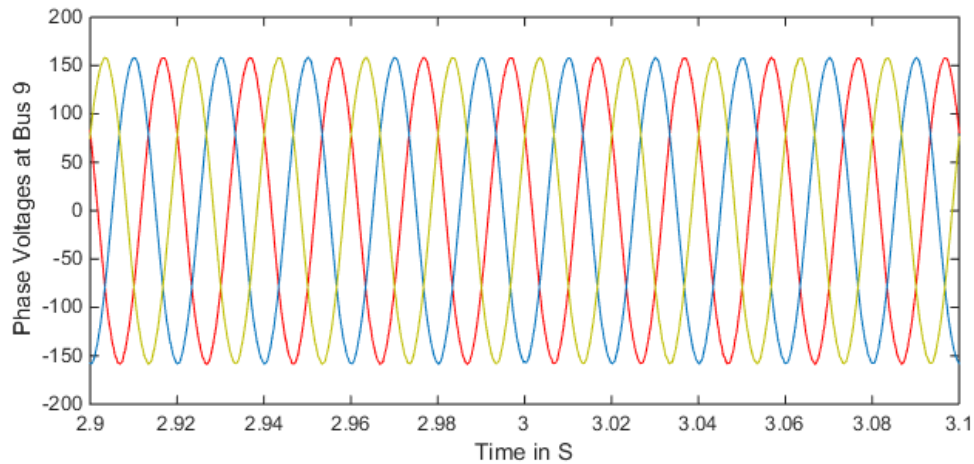
Fig. 8 Zoomed-in instantaneous phase voltages at bus number 9

The instantaneous phase voltages at bus number 1, slack bus is shown in Fig. 9 where as Fig. 10 shows the current flowing from bus 1. Since the load in the microgrid is changing at every 3s, the current at bus number 1 is changing accordingly, as shown in Fig. 9. However, the bus number 1 is a slack bus its voltage is almost uneffected, eventhough the short circuit MVA is cosidered as 1000MVA.
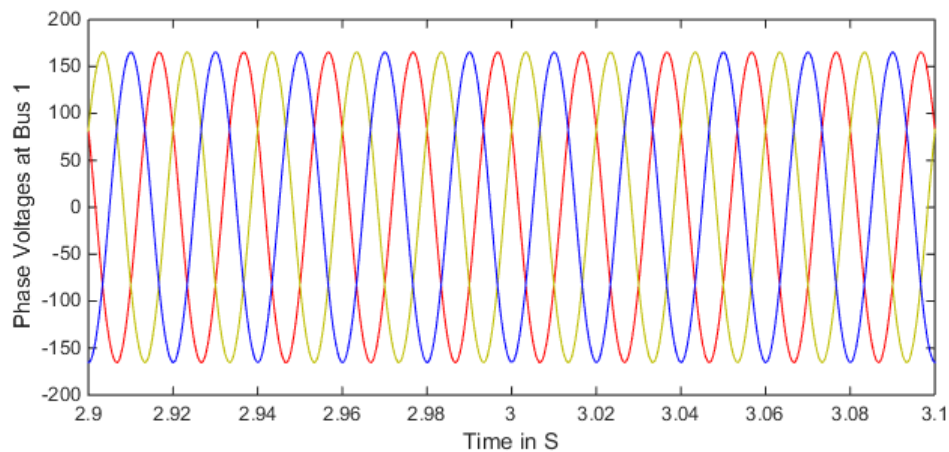
Fig. 9 Instantaneous phase voltages at bus number 1, Slack bus
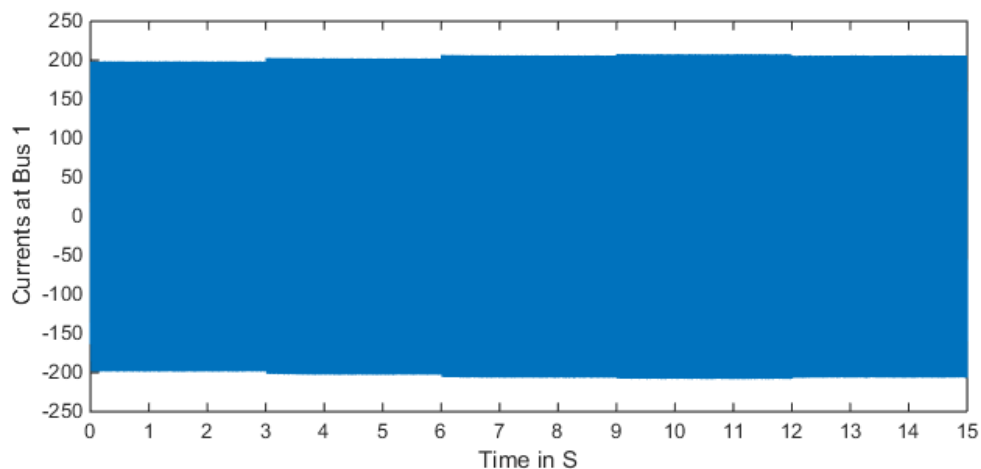
Fig. 10 Instantaneous phase currents at bus number 1, Slack bus

The following Fig. 11 given better understanding of changes in currents at bus number 1, which is a zoomed version of Fig. 10. Further, Fig. 12 depicts the instnataneous change in the current at bus number 1 at 3s.
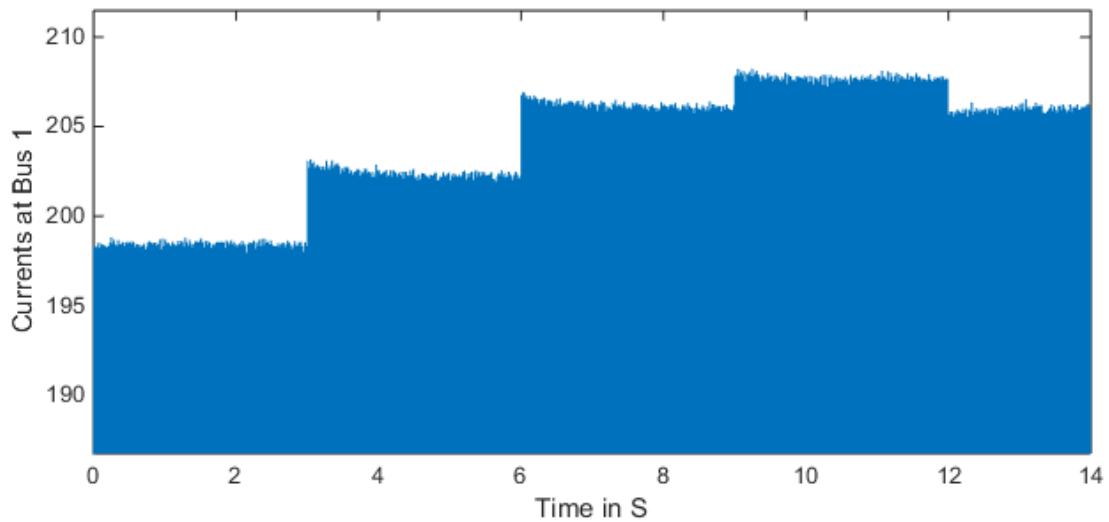
Fig. 11 Zoomed-in instantaneous phase currents at bus number 1, Slack bus
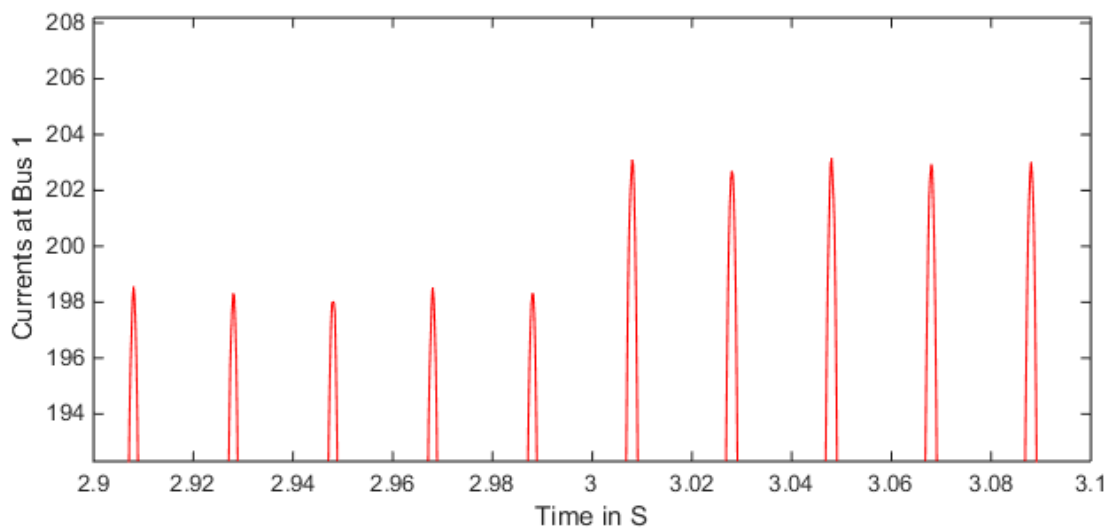
Fig. 12 Zoomed-in instantaneous phase currents at bus number 1 at 3s.
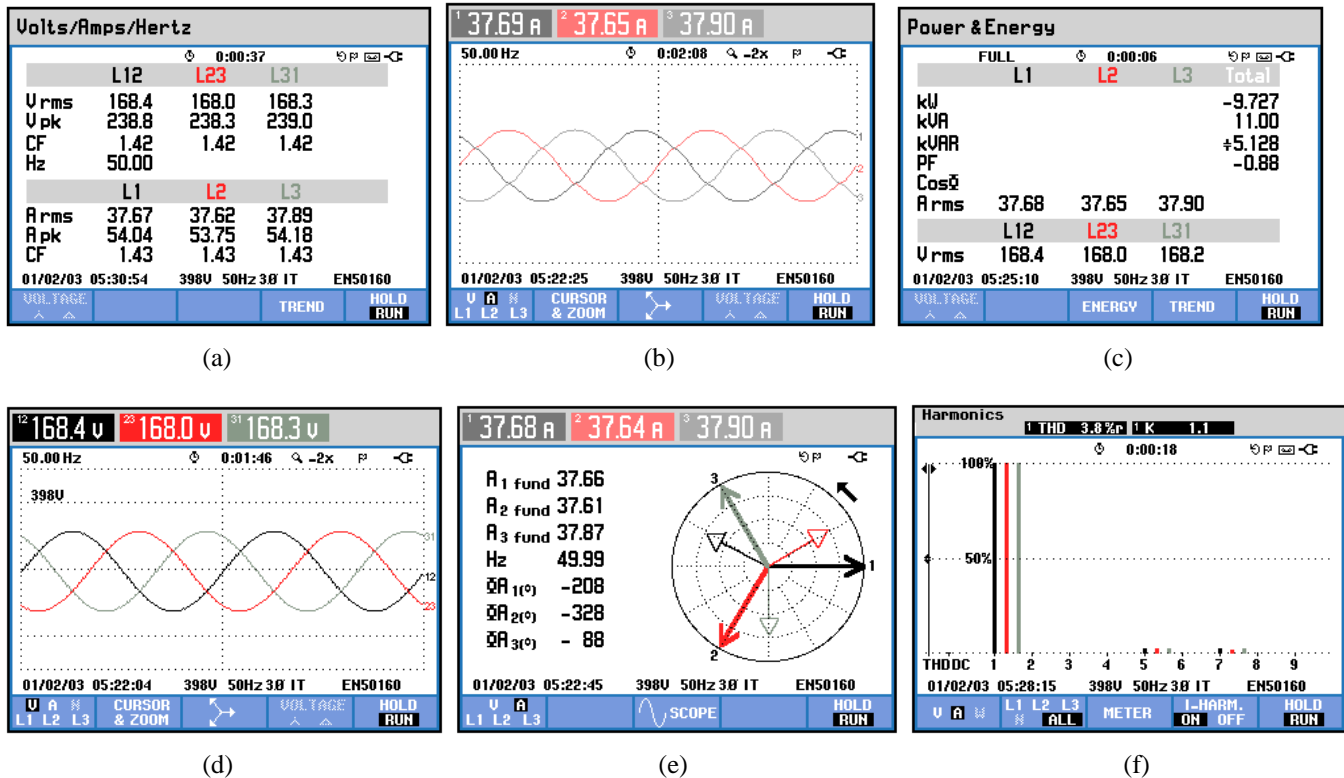
Fig. 13 Different electrical quantities at PV DG bus (at bus number 9). (a). Voltages and currents, (b). Instantaneous currents (c) Real and Reactive power feeding by PV DG at bus number 9 (d) Instantaneous voltages (e) Phasor diagram of voltages and currents (f). THD in the current fed by PV DG

Experiment-2: Microgrid system with PV generator at bus number 9 and PHEV/DC at bus number 5

As aforementioned, the PV DG is connected at bus number 9, whereas PHEV/DC is connected at bus number 5, the concluded optimal locations for respective DGs. According the optimal scheduling DGs are controlled to deliver, 10KW at 0.9 pf lead by PV DG and the PHEV/DC is controlled to deliver 6KW at 0.9pf lead.

In experiment-1, the bus 11 voltge is 192.4V, where in experiment-2, the same bus is experienceing a voltage of 194.2V as shownin Fig. 14.
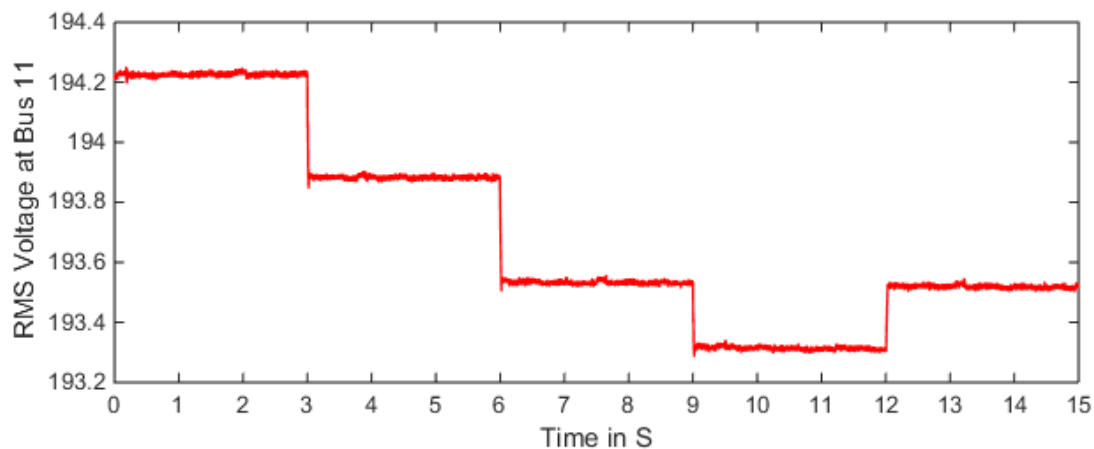
Fig. 14 RMS Line Voltage at bus number 11 with two DGs

It is due to the reason that, in experiment-1, only one DG is connected and the power generation within the DG is only 10kW, where as in experiment-2, the generation within the sources is 10KW+6KW. Due to the increased generation within the microgrid, the power, hence the current drawn from slack has decreased which results in reduction of drops, therefore the increase of bus voltage from 192.4v to 194.2V.

The following Figs. 15 and 16 represents the voltages at bus number 9, where the PV DG is interfaced. The voltage and currents at bus 1 are shown in Figs. 17 and 18. The zoomed-in currents is shown in Fig. 19 whereas Fig. 20 depicts the inatnateous change in current at 3s for the bus number 1.
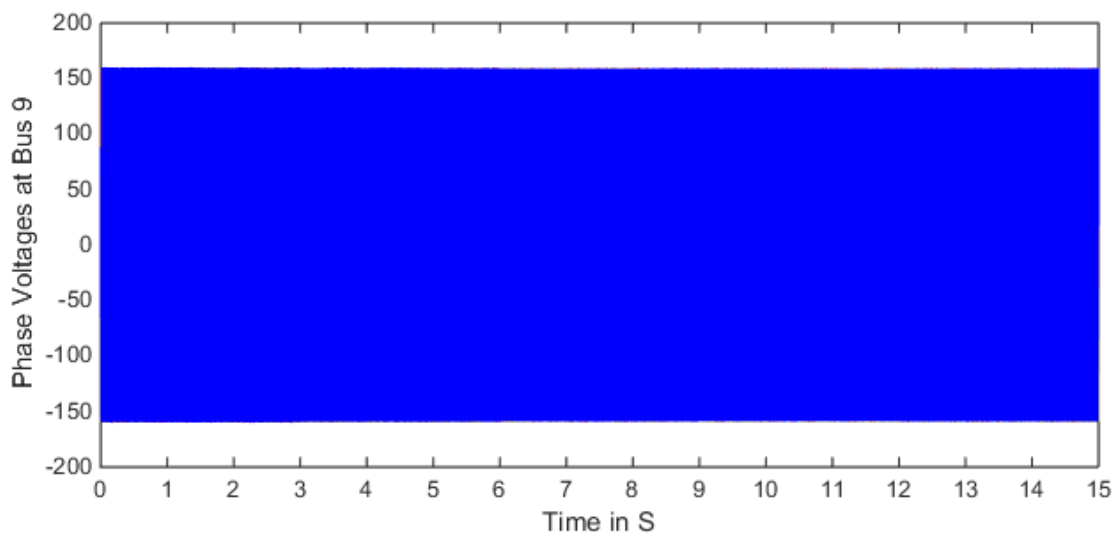
Fig. 15 Instantaneous phase voltages at bus number 9 with two DGs in the microgrid
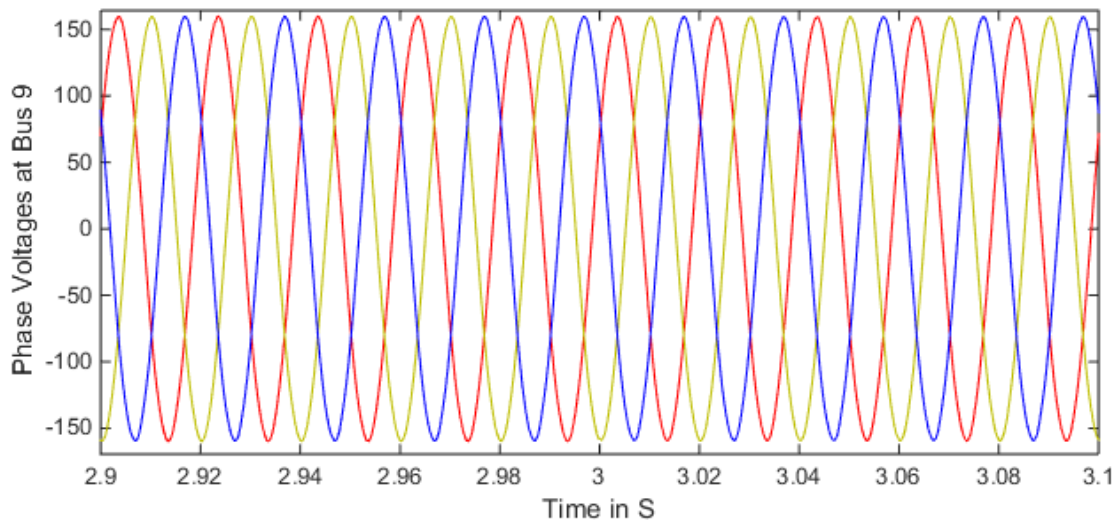
Fig. 16 Zoomed-in Instantaneous phase voltages at bus number 9 with two DGs in the microgrid
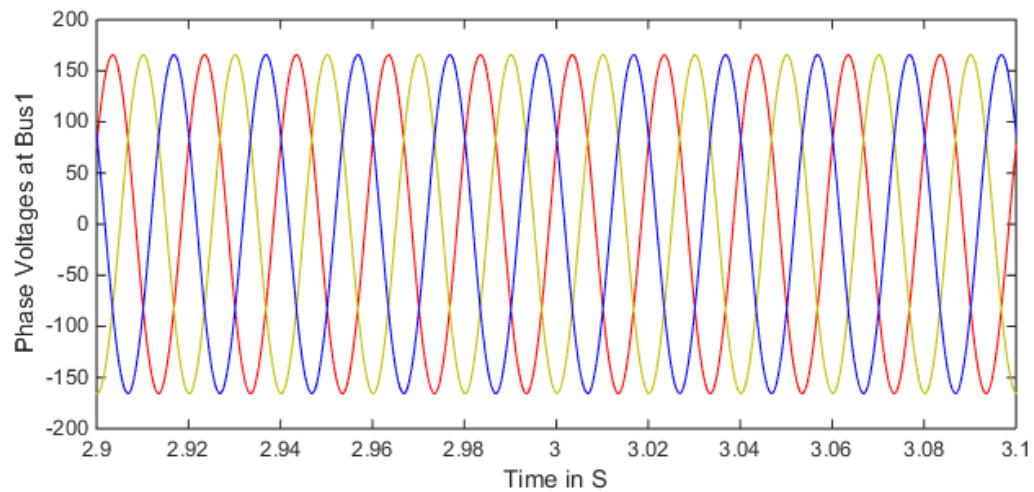
Fig. 17 Instantaneous phase voltages at bus number 1, Slack bus, with two DGs within the microgrid
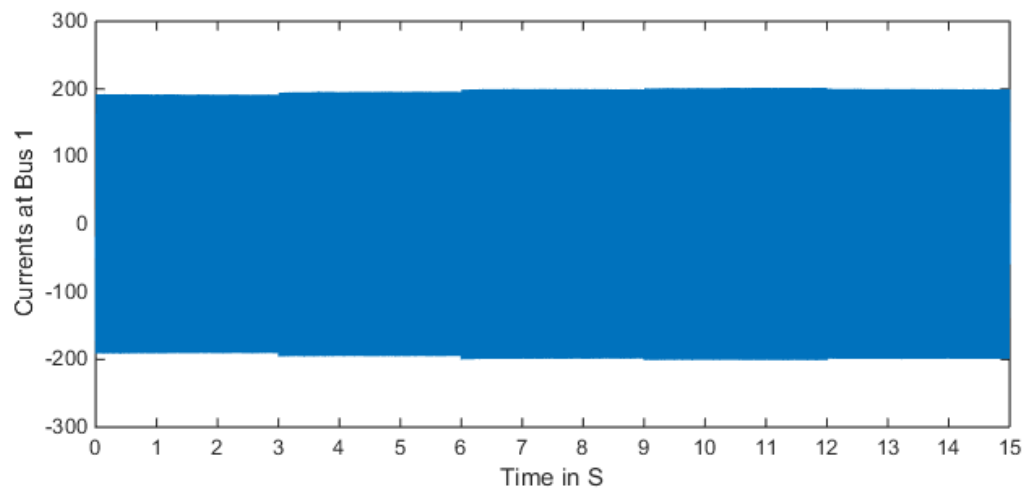
Fig. 18 Instantaneous currents at bus number 1, Slack bus, with two DGs within the microgrid
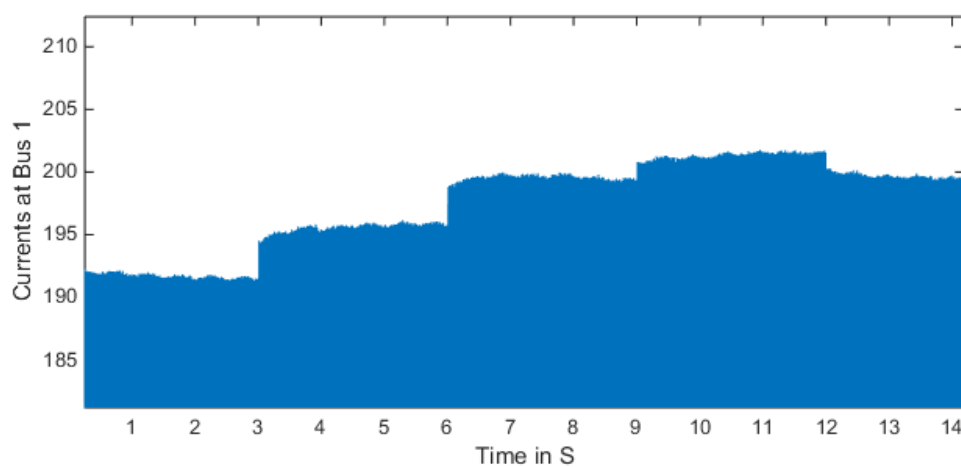
Fig. 19 Zoomed-in instantaneous phase currents at bus number 1, Slack bus, with two DGs interface within the microgrid

It can be inferred that, in experiment-1, since only DG is there in the microgrid, the microgrid is drawing more current, (198A peak) from slack bus. However, in experiment-2, since two DGs are there within the microgrid, the current drawn from the microgrid has decreased from 198A peak to 191.5A peak which is clearly depicted in Figs. 19 and 20.
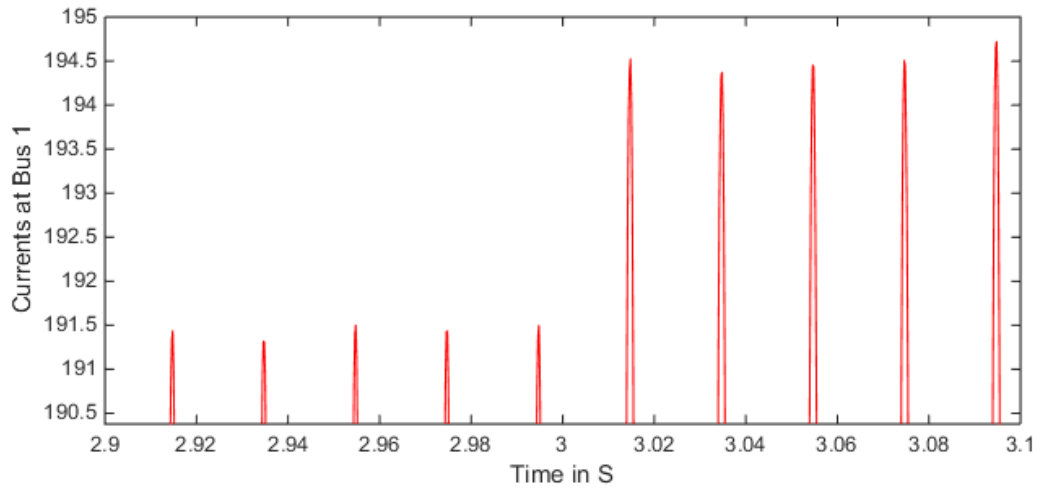
Fig. 20 Zoomed-in instantaneous phase currents at bus number 1 at 3s with two DGs within the microgrid

The instantaneous bus voltage at bus number 5 at which the second DG that is PHEV/DC is shown in Fig. 21. The actual currents, voltages at bus number 5 and the power fed by PHEV/DC at bus number 5 is shown in Fig. 22.

Since, the PV DG remains connected at bus number 9 with unchanged power feedings as shown in Fig. 13, the electrical quatities at bus number 9 is not given here. However, it can be observed from Figs. 13 and 22 that the volatge at bus number 5 is greater than the voltage at bus number 9. It is due to the reason that the bus 5 is electrically nearer to the slack bus when comapred to bus number 11 which can be observed from Fig. 1.
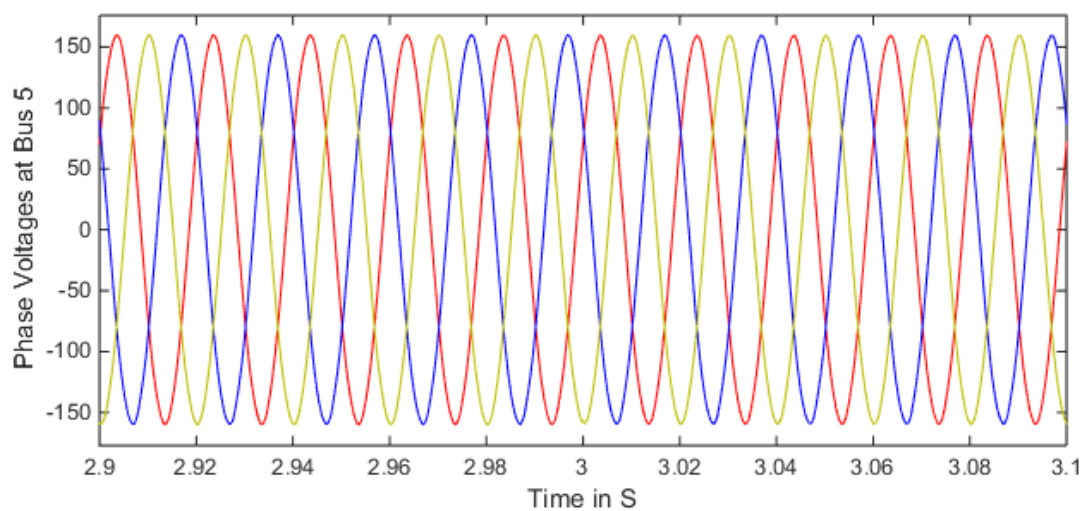
Fig. 21 Instantaneous phase voltages at bus number 5 with two DGs within the microgrid
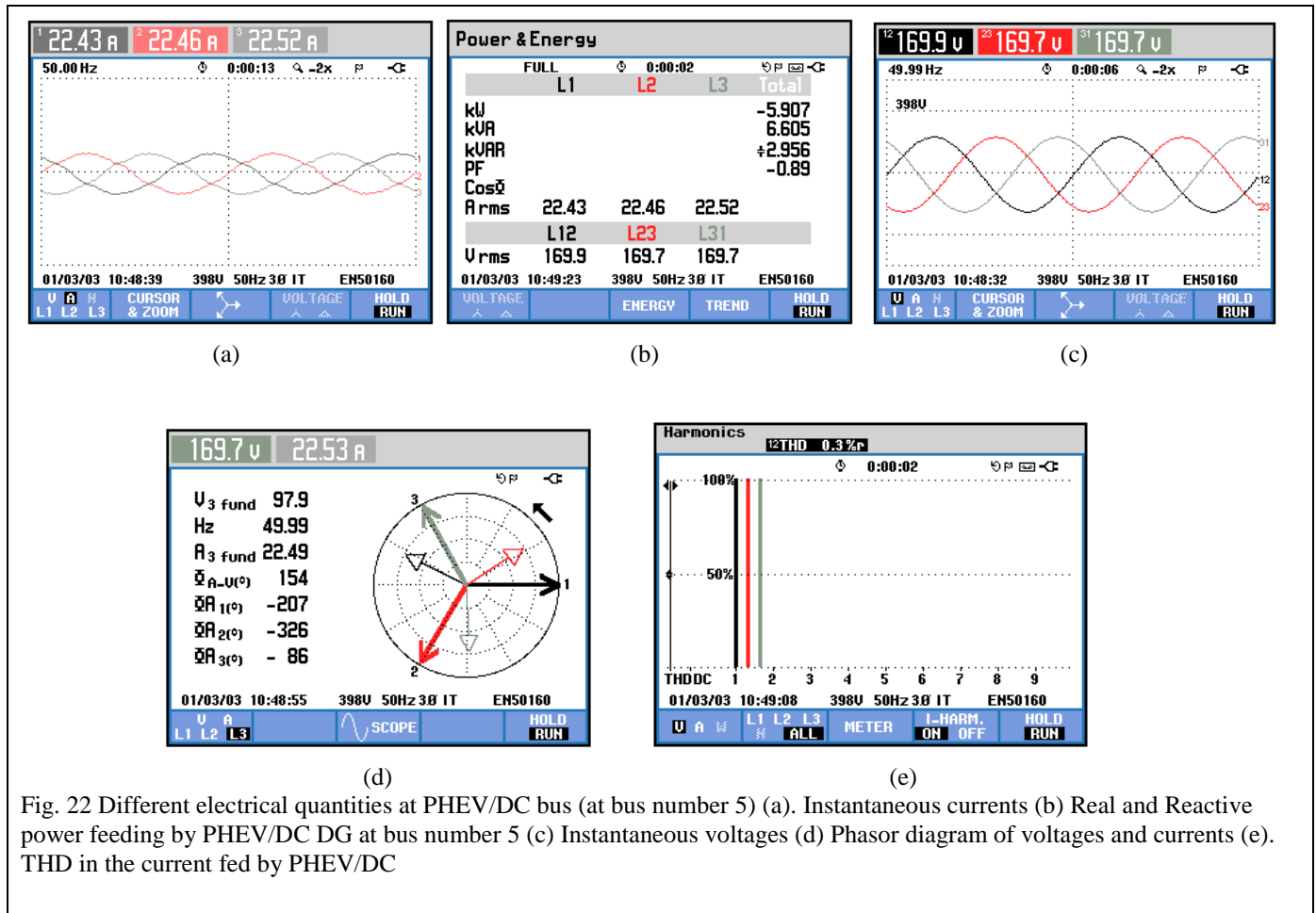
Fig. 22 Different electrical quantities at PHEV/DC bus (at bus number 5) (a). Instantaneous currents (b) Real and Reactive power feeding by PHEV/DC DG at bus number 5 (c) Instantaneous voltages (d) Phasor diagram of voltages and currents (e). THD in the current fed by PHEV/DC

HOST RESEARCH INFRASTRUCTURE UTILIZED

This project utilized the following equipment/devices/research infrastructure at the host institute.

1. Power Hardware-in-Loop systems/Opal-RT Systems

2. Microgrid Set-up with two converter based distributed generators to act as PV and Battery of Plug-in-Hybrid Electric Vehicle/Data Centre

3. Grid Emulator/Grid interfacing Infrastructure

4. Other basic infrastructure of Power engineering Laboratory, like power supplies with proper protection, metering and measuring devices, etc.

Conclusion

In the emerging trend of increasing renewable penetration, reliability plays a critical role for successful realization and operation of microgrids. In this connection, this project considered a European Medium Voltage distribution system with two different DGs, PV and PHEV/DC for the improvement of reliability.

With an objective of improving the reliability of the considered microgrid system, an optimal DG schedules have been found using metaheuristic optimization algorithm known as bat algorithm. System loss, cost and voltage deviations have been minimized while finding the optimal DG schedules for improving the reliability.

The optimal schedules calculated are validated for their practical feasibility through experimentation using the Power-hardware-in-loop with the help of Opal-RT system integrated with real power electronic converter based DGs and grid emulator based interface.

After successful experimentation, the calculated schedules can be practically feasible and successful integration of DGs with scheduled power flows can be achieved to improve the reliability.

Acknowledgement

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