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Multi-Agent Supervisory Control for Optimal Economic Dispatch in DC Microgrids

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Abstract

Global warming has stimulated researchers' interests in coming up with alternative sources of energy and transportation facilities with less emission. DC distribution systems are an attractive candidate to adapt high penetration of distributed generation and electric vehicles. Accordingly, this work proposes multi-agent supervisory control for optimal power dispatch in DC distribution systems. The algorithm offers the additional advantage of the ability to restore the average system voltage to its nominal value. The incorporation of DG droop-based control renders the proposed algorithms fully distributed. Real-time OPAL-RT simulations demonstrate the effectiveness of the proposed algorithm in a hardware-in-the-loop (HIL) application.

Keywords: DC microgrids, distributed power management, real-time simulations, supervisory control.

1. Introduction

The radical changes in the ratio of AC and DC loading and generation blend have stimulated a new request for practical implementation of DC distribution systems. Thus, DC networks have recently been revived as a new concept in ADNs under the smart grid paradigm. On one hand, electronic loads have invaded all modern homes. New high-efficient and high-quality DC lighting systems have been invented. Major loads such as modern elevator motors operate nowadays based on variable speed drives. In addition, PEV technology will be crucial in future electric distribution systems. On the other hand, it would be more economical if renewable energy resources such as wind and photovoltaic (PV), as well as energy storage systems, are integrated into DC rather than AC systems. Further, fuel cell units making use of biomass fuel with DC output voltage is a rising technology. DC systems also have the intuitive merits of reducing interference with AC grids and facilitating the expansion of power capacity. One of the important study issues in autonomous microgrid is power management, which is directly related to DG voltage regulation.

The economic performance is an important aspect in the successful operation of microgrids. Many publications has tackled centralized economic dispatch algorithms in ac microgrids [1]–[3]. In addition, recent publications have triggered decentralized economic dispatch problem [4], [5]. However, to the authors' best of knowledge, all the decentralized algorithms proposed in literature tailored based on all system generation and load nodes are agents in order to eliminate any mismatch between generation and loads.

This paper proposes a hierarchical control for DC microgrids. The DG primary controller is the common V/I droop that operates as an initial step to maintain balance between the generation and the loads. The proposed supervisory control is based on multi-agent algorithm that adapt the DG reference setting in order to achieve precise economic dispatching via a proposed distributed equal incremental cost (DEIC) algorithm. DEIC relies on average consensus among agents and have the potential to restore the system voltage to its nominal setting as an additional advantage.

Thanks to the droop characteristic, agents are assigned to DG buses only without the need for assigning extra agents at load buses. That proposed structure entails less implementation cost. In addition the proposed algorithms are fully decentralized since each DG locally discovers its appropriate update. Compared to centralized supervisory controller [6], the proposed algorithm has the potential of i) more economical with low communication and computational requirements, ii) the utilization of local information to carry out the algorithms. In order to verify the proposed algorithm performance, real-time validation is performed through a hardware-in-the-loop (HIL) application, with precise performance obtained.

2. Control hierarchy overview

2.1 Primary control

The DGs' primary controller in this work is based on the current droop control, Fig. 1. The main advantage of this scheme is the capability to enhance the current sharing without any communication. Equ. (1) is the droop equation which aims to reduce the DG voltage with increasing the DG current in order to stimulate the other DGs that are cooperating in the sharing process.

$$\boldsymbol{v} = \boldsymbol{v}^* - \boldsymbol{r}\,\boldsymbol{i} \qquad (\mathbf{1})$$

Where: v^* is the DG reference (no-load) voltage setting, v, i are the DG output voltage and current respectively and r is the droop gain.

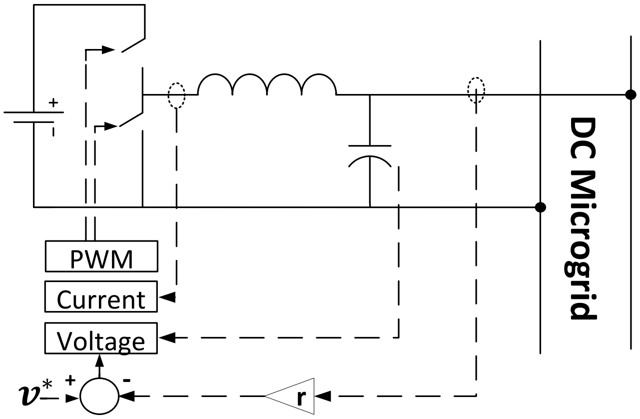


Figure 1 V/I droop control

2.2 Supervisory control

The main objective of the distributed supervisory control action is to achieve precise equal incremental cost and adjust the DG voltage levels according to the loading condition by updating each of the DGs' no load reference voltages. For instance, without losing generality, the equal incremental cost is considered among DG units with the same ratings and incremental cost functions. For a set of N buses we assume the first N_g are the DG buses and $N_g + 1$ to N to be assigned to constant power loading buses. The target of the supervisory control is to derive the system to a steady state condition defined in (2) and (3).

$$\begin{gathered}
\boldsymbol{p} = \boldsymbol{v_1} \sum_{\boldsymbol{k} \in \boldsymbol{B}} \boldsymbol{Y_{1,k}}\, \boldsymbol{v_k} \\
\vdots \\
\boldsymbol{p} = \boldsymbol{v_{N_g}} \sum_{\boldsymbol{k} \in \boldsymbol{B}} \boldsymbol{Y_{N_g,k}}\, \boldsymbol{v_k} \\
\boldsymbol{p_{N_g+1}} = \boldsymbol{v_{N_g+1}} \sum_{\boldsymbol{k} \in \boldsymbol{B}} \boldsymbol{Y_{(N_g+1),k}}\, \boldsymbol{v_k} \\
\vdots \\
\boldsymbol{p_N} = \boldsymbol{v_N} \sum_{\boldsymbol{k} \in \boldsymbol{B}} \boldsymbol{Y_{N,k}}\, \boldsymbol{v_k}
\end{gathered} \qquad (\mathbf{2})$$

$$\boldsymbol{mean}\left(\boldsymbol{v_1} + \cdots + \boldsymbol{v_{N_g}}\right) = \boldsymbol{v^{setting}} \qquad (\mathbf{3})$$

Where p_k, v_k are the power and voltage at bus k, respectively. *Y* is the bus admittance matrix of the system. B is a set of all the system buses. $v^{setting}$ is the reference system voltage setting.

3. Sensitivity analysis

The following analysis relates the required change in the DGs' reference voltage to obtain the desired change in the DGs' bus voltages and currents. The main equations that relate DGs' reference and system voltages and currents flow can be written in compact form as:

$$\boldsymbol{V^*} = \boldsymbol{V_g} + \boldsymbol{R I_g} \qquad (\mathbf{4})$$

$$\boldsymbol{I} = \boldsymbol{Y}\, \boldsymbol{V} \qquad (\mathbf{5})$$

Where V^*, V_g, and $\mathrm{I_g}$ are vectors of DGs' reference voltages, voltages and currents, respectively. *R* is a diagonal $N_g \times N_g$ matrix with element $R(j,j) = r_j$ (DG j droop gain).

In incremental form:

$$\Delta \boldsymbol{V^*} = \Delta\, \boldsymbol{V_g} + \boldsymbol{R}\, \Delta \boldsymbol{I_g} \qquad (\mathbf{6})$$

$$\Delta \boldsymbol{I} = \boldsymbol{Y}\, \Delta \boldsymbol{V} \qquad (\mathbf{7})$$

Equation (7) can be written with partitioning system buses into DG buses and load buses as:

$$\begin{bmatrix} \Delta \boldsymbol{I_g} \\ \Delta \boldsymbol{I_l} \end{bmatrix} = \begin{bmatrix} \boldsymbol{Y_{gg}} & \boldsymbol{Y_{gl}} \\ \boldsymbol{Y_{lg}} & \boldsymbol{Y_{ll}} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{V_g} \\ \Delta \boldsymbol{V_l} \end{bmatrix} \qquad (\mathbf{8})$$

where V_l, I_l are vectors of load buses voltages and currents, respectively.

Assuming no change in the current of loads, i.e. $\Delta I_l = 0$:

The change in the reference voltage to handle the DG units voltages and current can be concluded as:

$$\Delta \boldsymbol{V^*} = \left(\boldsymbol{S_d}^{-1} + \boldsymbol{R}\right) \Delta \boldsymbol{I_g^{req}} + \boldsymbol{1_{Ng}}\, \Delta \boldsymbol{v^{req}} \qquad (\mathbf{9})$$

$$\boldsymbol{S_d} = \boldsymbol{S} + \overline{\propto} \tag{10}$$

With,

$$\boldsymbol{S} = \boldsymbol{Y_{gg}} - \boldsymbol{Y_{gl}} \boldsymbol{Y_{ll}}^{-1} \boldsymbol{Y_{lg}}$$

$$\overline{\propto} = \left(\mathbf{1}_{Ng} \begin{bmatrix} \propto_1 & \propto_2 & \cdots & \propto_N \end{bmatrix}\right)^{T}$$

4. Supervisory control algorithm

The proposed supervisory algorithm has been defined based on distributed control technology, where DG units are considered as control agents that exchange information synchronously. The supervisory control cycle is illustrated in Fig. 2. Every cycle starts by a delay period which is a number of iterations in which the DG unit do not exchange information to have the chance to change their states after the last firing action. Subsequently, the DGs start to share information for a predefined enough number of iterations to reach the consensus state (all agents have the same value of a certain variable of interest). Finally each DG applies the appropriate modification on its reference voltage based on the information on which consensus has been obtained.

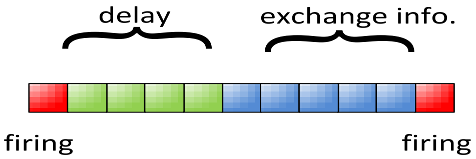


Figure 2 Supervisory control operation cycle

5. Exchange of information overview

In isolated DC microgrid different DGs are assumed to share some variables according to the active consensus algorithm (DEPS). The flow of data among the DGs can be modelled as a weighted directed graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}, \mathcal{W}\}$, Fig. 3. Where $\mathcal{V} = \{1,2,\ldots,\mathrm{n}\}$ is the set of vertices (DGs in our case). $\mathcal{E} \in \mathcal{V} \times \mathcal{V} \backslash \mathrm{diag}(\mathcal{V})$ is the set of directed edges with connectivity weight defined as $\mathcal{W}$; In other words $(u,t) \in \mathcal{E}$ is a direct edge from u to t if the weight of connectivity $\mathcal{W}_u^t > 0$. To line up with literature, self-loops are not counted in $\mathcal{E}$. The neighbors of node u are the nodes that can send and receive information to and from the node u. They are denoted as $\mathcal{N}_u = \{l \in \mathcal{V}: \{(l,u),(u,l)\} \in \mathcal{E}, and\ l \neq u\}$.

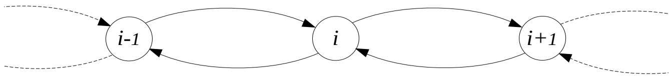


Figure 3 Communication network graph

6. Distributed equal incremental cost algorithm (DEIC)

The typical economic dispatch problem can be defined as

$$\mathbf{min} \sum_{\mathbf{u} \in \mathbf{G}} \mathbf{OC_u(p_u)} \qquad (11)$$

subject to the following:

A generation and loading equality constraint:

$$\sum_{u \in G} \boldsymbol{p_u} = \sum_{d \in L} \boldsymbol{p_d} \qquad (12)$$

A DG minimum and maximum output power constraint:

$$\mathbf{p_u^{min} \le p_u \le p_u^{max}} \ \ \forall\, \mathbf{u} \in \mathbf{G} \qquad (13)$$

where G and L are the sets of DG and load buses, respectively. $\mathrm{OC_u}$, $\mathrm{p_u^{min}}$, and $\mathrm{p_u^{max}}$ are $\mathrm{DG_u}$ operating cost, and $\mathrm{DG_u}$ minimum and maximum power limits, respectively.

The DG operating costs are assumed to be quadratic, as is the common practice reported in the literature. The incremental cost thus becomes a linear function:

$$\mathbf{OC_u(p_u) = a_u + b_u P_u + \ c_u\ P_u}^{\mathbf{2}} \qquad (14)$$

$$\boldsymbol{\lambda}_\mathbf{u} = \mathbf{b_u + 2\ c_u\ P_u} \qquad (15)$$

where λ_u is the incremental cost for $\mathrm{DG_u}$. The aforementioned optimization Problem is a well-known economic dispatch problem [7]. Since it is a quadratic convex problem, it has a unique optimal solution that satisfies the following:

$$\begin{cases} \boldsymbol{\lambda_u = \lambda^*} & \boldsymbol{if} \quad \boldsymbol{p_u^{min} < p_u < p_u^{max}} \\ \boldsymbol{\lambda_u \ge \lambda^*} & \boldsymbol{if} \qquad\quad \boldsymbol{p_u = p_u^{min}} \\ \boldsymbol{\lambda_u \le \lambda^*} & \boldsymbol{if} \qquad\quad \boldsymbol{p_u = p_u^{max}} \end{cases} \qquad (16)$$

Where λ^* is the optimal incremental cost for DG units that are not operating at their limit.

The implementation of droop characteristics implies that all DG units share the total load so that (12) is always satisfied. The power limit constraint, as defined by (13), is also guaranteed by the DG current control. Eq. (16) can be interpreted as a sufficient condition for a group of DG units to operate with optimal operating costs. In other words, by obtaining the average incremental cost (λ_{avg}) of all of the DG units that are not working at their limit, each DG can change its output power so that it operates at an incremental cost close to λ_{avg}.

As with DEPS, DEIC must produce an average consensus of a set of variables μ, Γ,and Ψ, which are defined initially as follows:

$$\boldsymbol{\mu_u}[\mathbf{0}] = \begin{cases} \boldsymbol{\lambda_u} & \boldsymbol{if} \qquad \boldsymbol{u \in \rho} \\ \mathbf{0} & \qquad \boldsymbol{otherwise} \end{cases} \qquad (17)$$

$$\boldsymbol{\Gamma_u}[\mathbf{0}] = \begin{cases} \mathbf{1} & \boldsymbol{if} \qquad \boldsymbol{u \in \rho} \\ \mathbf{0} & \qquad \boldsymbol{otherwise} \end{cases} \qquad (18)$$

$$\boldsymbol{\Psi_u}[\mathbf{0}] = \boldsymbol{v_u} \qquad (19)$$

where ρ is a set of DG units that operate within their power limits; i.e., $\mathrm{DG_u} \in \rho \quad \text{if} \quad \mathrm{p_u^{min}} < \mathrm{p_u} < \mathrm{p_u^{max}}$. The above initial $\mu, \Gamma, \text{and}\ \Psi$ values are updated. After sufficient iterations, the average incremental cost can be obtained:

$$\lambda_{avg} = \lim_{k\to\infty} \frac{\mu_u[k]}{\Gamma_u[k]} = \frac{\sum_{t\in\rho} \lambda_t}{|\rho|} \quad (20)$$

$$v^{sys} = \lim_{k\to\infty} \Psi_u[k] = \frac{\sum_{t=1}^{N_g} v_t}{N_g} \quad (21)$$

The average system voltage v^{sys} can be estimated using (21). Based on (20), each agent can determine the appropriate change in its output power so that it approaches the desired λ_{avg}, as follows:

$$\Delta\, p_u^{req} = \frac{(\lambda_{avg} - \lambda_u)}{2\, c_{max}} \quad (22)$$

where c_{max} is a common constant for all DG units that satisfies

$$\frac{N_g}{N_g - 1} c_{max} \geq\ c_1, c_1, \dots, c_{N_g} \quad (23)$$

This condition guarantees that all DG units converge to an optimal solution. In the work presented in this paper, c_{max} is chosen to be the largest DG quadratic coefficient of all of the OC functions. The changes in DG output currents and voltages required for guaranteeing equal incremental cost operation and for restoring the average system voltage can then be determined using (24) and (25).

$$\Delta i_u^{req} = \frac{\Delta\, p_u^{req}}{v_u + \Delta v^{req}} \quad (24)$$

$$\Delta v^{req} = v^{nom} - v^{sys} \quad (25)$$

These changes can be realized through appropriate adjustments to all DG no-load voltages, using (9).

7. Real time simulation

Real time simulations are performed to demonstrate the effectiveness of the proposed consensus algorithm. A dc microgrid is modeled in the RT-LAB® simulator using the SimPowerSystems® blockset and ARTEMiS® plug-in from OPAL-RT. The RT-LAB simulator provides a parallel computation which allows distributing large and complex models over several processors to perform powerful computations with high accuracy and low cost real-time execution. The RT-LAB simulator is used to perform two main functions. First, Rapid Control Prototyping (RCP) realization in which the DG hierarchical control, i.e. DG primary and secondary control, is implemented to mimic DG actual controllers. Compared to DG actual controllers, RCP controllers are more flexible, easier to debug and faster to implement. Second, Hardware-in-the-Loop realization in which DG physical controllers, which are implemented as RCP controllers, are connected to the virtual DC microgrid executed in real time. The DEIC is tested by arbitrary choosing the initial voltage reference for each DG units as 413,400,407, and 400 respectively. Figures 5-7 illustrate the DG output voltage and power for 50 second period. During that period the DEIC algorithm is activated, a sudden decrease in load and a sudden increase in load occur at 5, 18, and 34 seconds, respectively. At change times a zoomed windows (A, B and C) are stretched downwards at Figure 8 to capture the transient performance.

Before DEIC activation, the DG output power was not satisfying the minimum operating cost condition (Equal incremental cost criteria) and the system average voltage was below the nominal 400 voltage by 8 volts. As illustrated in Figure 8(A), activation the DEIC stimulates the DG units to operate at equal incremental cost condition and raise the system voltage to the nominal 400 voltage. Figure 8(B) shows the DEIC algorithm performance at a sudden decrease of load. The DEIC algorithm drives the DG output power back to equal incremental cost and reduce the system voltage to the nominal 400 voltage after the load decrease. The opposite situation is illustrated via sudden load increase in Figure 8(C).

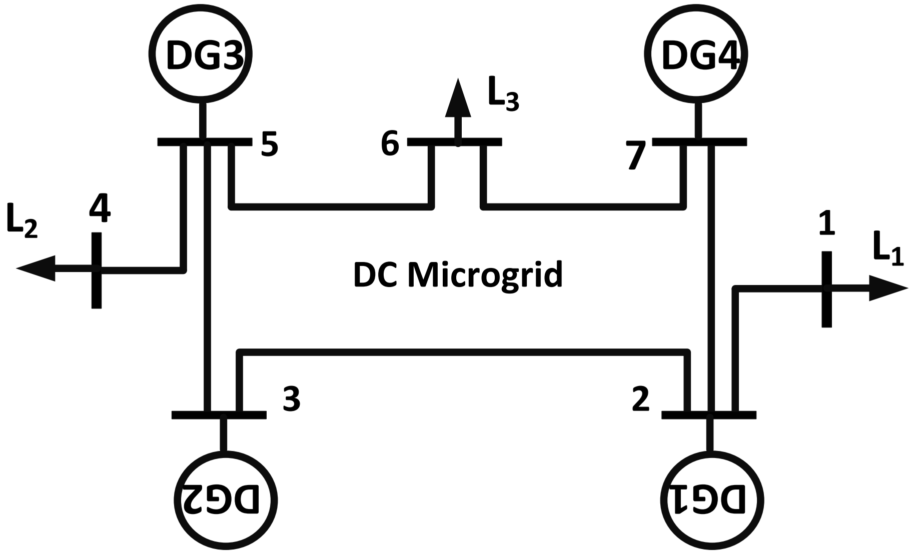


Figure 4 Schematic diagram for the test system under study

Table 1: DATA for the system

F	T	Res. (Ω)	Ind (mH)
1	2	0.02	0.045
2	3	0.1	0.23
4	5	0.02	0.045
3	5	0.2	0.45
5	6	0.05	0.11
6	7	0.05	0.11
7	2	0.2	0.45

Table 2: DGs DATA

Gen #	Bus #	a_u	b_u	c_u	p_u^{min} (KW)	p_u^{max} (KW)	Droop (Ω)
G1	2	5.0797	0.0792	0.0005	20	100	0.08
G2	3	0.8505	0.0689	0.0009	10	80	0.1
G3	5	2.0249	0.0301	0.0011	20	100	0.08
G4	7	3.5442	0.1189	0.0003	10	100	0.08

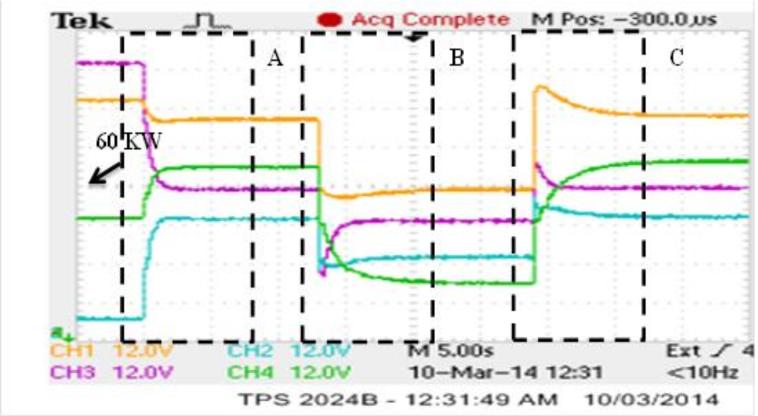


Figure 5 DG output power in case of operation according to the DEIC algorithm. Horizontal scale: 5 s/div; vertical scale: 12 kW/div.

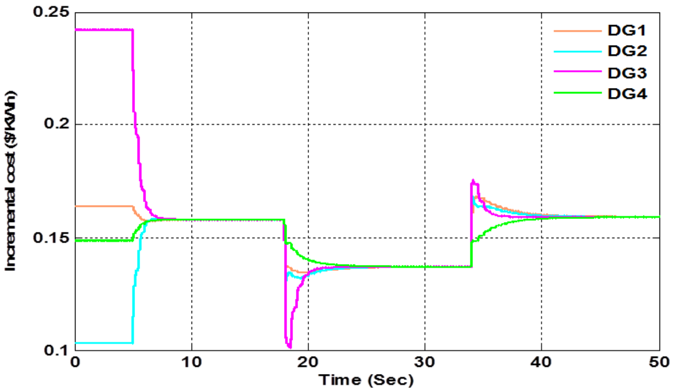


Figure 6 DG incremental cost in case of operation according to the DEIC algorithm.

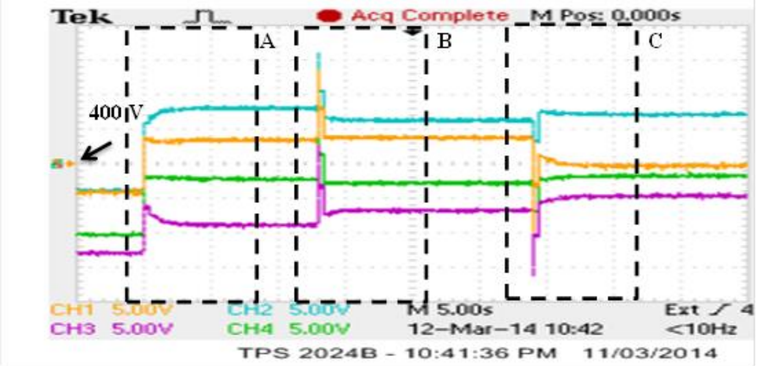
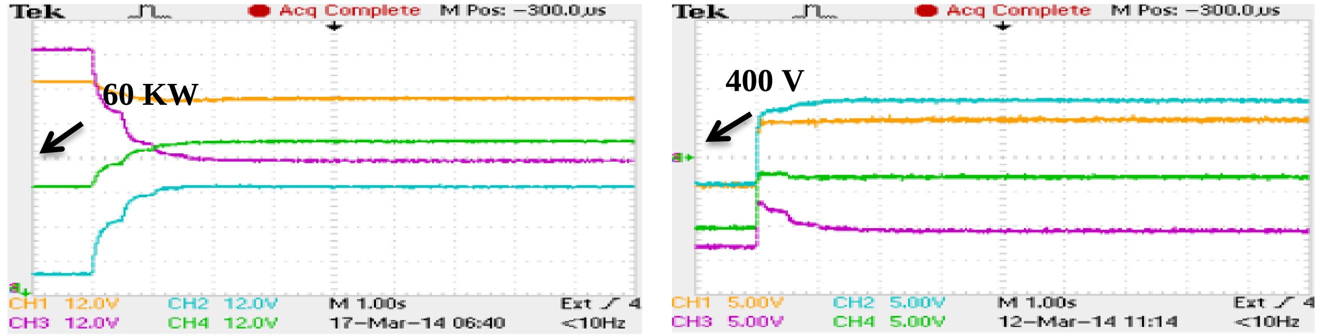


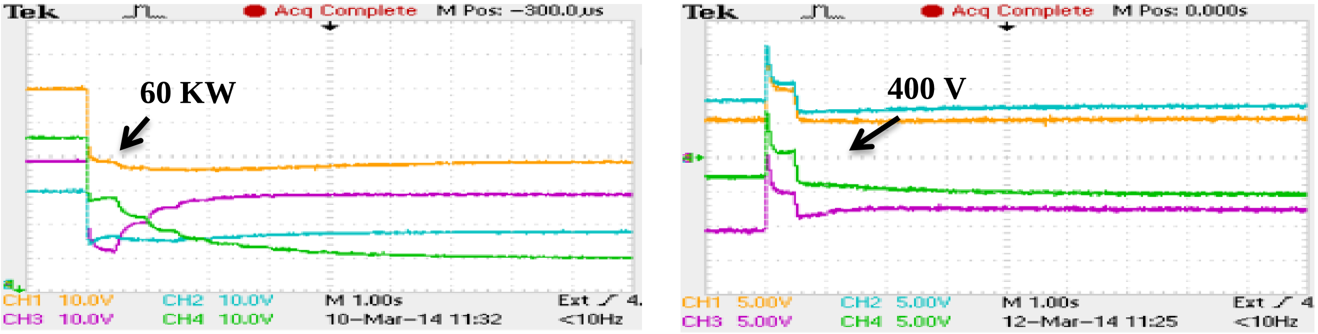
Figure 7 DG output voltage in case of operation according to the DEIC algorithm. Horizontal scale: 5 s/div; vertical scale: 5 V/div.

(A)



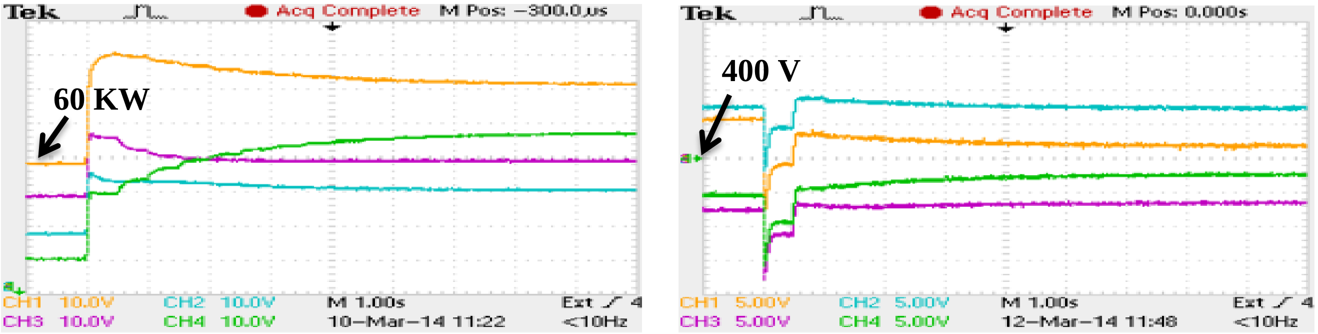
Horizontal scale: 500ms/div; vertical scale: 12 kW/div. **Horizontal scale: 500ms/div; vertical scale: 12 kW/div.**

(B)



Horizontal scale: 500ms/div; vertical scale: 12 kW/div. **Horizontal scale: 500ms/div; vertical scale: 12 kW/div.**

(C)



Horizontal scale: 500ms/div; vertical scale: 12 kW/div. **Horizontal scale: 500ms/div; vertical scale: 12 kW/div**

Figure 8 DG output power and voltage in case of operation according to the DIEC

5. Conclusion

In this work a supervisory control algorithm is proposed to tackle the economic dispatch problem in isolated DC microgrids, utilizing the proposed average consensus algorithm. The algorithm precisely drives the DG units to operate under equal incremental cost. In addition, the algorithm assists in regulating the system voltage as an additional advantage. Simplicity of the proposed algorithm can be counted as a key advantage towards a practical implementation.

8. References

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