Distributed Control and Management of Renewable Electric Energy Resources for Future Grid Requirements

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Chapter 1

Distributed Control and Management of Renewable Electric Energy Resources for Future Grid Requirements

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Abstract

It is anticipated that both medium- and low-voltage distribution networks will include high level of distributed renewable energy resources, in the future. The high penetration of these resources inevitably can introduce various power quality issues, including; overvoltage and overloading. This book chapter provides the current research state of the art concepts and techniques in dealing with these potential issues. The methods provided in this chapter are based on distributed control approach, tailored and suitable particularly for the future distribution composition. The distributed control strategy is a promising approach to manage and utilise the resources in future distribution networks to effectively deal with grid electric quality issues and requirements. Jointly, utility and customers the owners of the resources in the network are considered as part of a practical coordination strategy in this method. Standard IEEE test system is used for application, and to demonstrate the effectiveness of the method by providing the results.

Keywords: distributed control, consensus algorithm, energy storage system (ESS), future grid requirements, network overloading

1. Introduction

Distribution networks are usually designed to provide electric power to the customers, while operating within the grid national electricity standards, in particular having voltage and loading in permissible range. The existing distribution network planning, design and operation usually does not consider the existence of renewable energy sources such as

Photovoltaic (PV) and wind turbine [1, 2]. Future distribution networks with high utilisation of these resources will have to meet certain requirements addressing issues such as voltage and equipment loading [2, 3]. Therefore, new facilities, methods and strategies have to be envisaged for proper design, operation and planning of future distribution networks.

Literature offers numerous methods and strategies that are designed to deal with the future network requirements. Resources such as renewable energy sources, storage systems and smart loads with practical and adequate control methods will play an important role in this regard. These resources can be utilised for various reasons by utilities and customers [4]. Among many utilisation of these facilities, network loading support is the main application addressed in this chapter. Due to the variety use of these resources, normally supervisory control could not deliver promising objectives due to the reliability and complexity issues [2]. On the other hand, neither local management approach could offer an efficient control strategy [2]. However, distributed control is found to be the most practical control strategy in application to future smart grid [1], particularly for distribution network [2]. This control approach has already been established for many applications as reported in recent research citations [3–7]. To have a distributed management of resources, the smart network usually includes two layers. The first layer as physical layer consist of grid lines and energy resources, while the second layer as the cyber layer is added to provide information exchange between the nodes. Distributed control strategy uses the immediate neighbouring communication information to control and manage energy resources.

The main aim of this book chapter is to provide some of the concepts and formulations used for distributed control, and to illustrate an application with results to support the method. In this approach, energy storage system (ESS) is considered as the promising facility for customers and utilities that can be used for different applications. Loading issue is considered as one of the network requirement which need to be dealt with using ESSs in distribution network. For all practical purposes, utility and/or customer are considered as the owner of storage facilities.

Section 2 discusses the main technical issues and influencing factors relating to the future state of distribution network operation with renewable energy resources. Distributed control management and its application in distribution network are put in perspective in Section 3. Distributed management of energy resources based on specific network requirement is discussed in Section 4. A case study using the distributed control strategy with detailed results is provided in Section 5. Finally, Section 6 concludes this chapter with related discussions and conclusions.

2. Future state of distribution networks with renewable energy resources

2.1. Power quality issues associated with high utilisation of renewable energy sources

Renewable energy sources will play an important role in future electricity grid. Depending on the geographical location and network structure, they may be in either off-grid or grid-

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connected situation. Despite the mode of network connection, economically speaking, the main purpose of these resources was to reduce electricity consumption cost. However, from the technical point of view, there is a difference between these two connecting modes. In off-grid mode, usually the main aim was to balance generation and load to avoid load outage, which is not desirable [8]. However, in grid-connected mode, as grid support is available, the unbalancing can be tolerated to some allowable extend. However, significant unbalancing between generation and load can induce power quality issues. To better understand these issues, **Figure 1** shows a single-line diagram of distribution network in which all customers' load and generation in each phase are modelled by single generation and load. Based on this model, different issues associated by renewable energy sources can be addressed as follow:

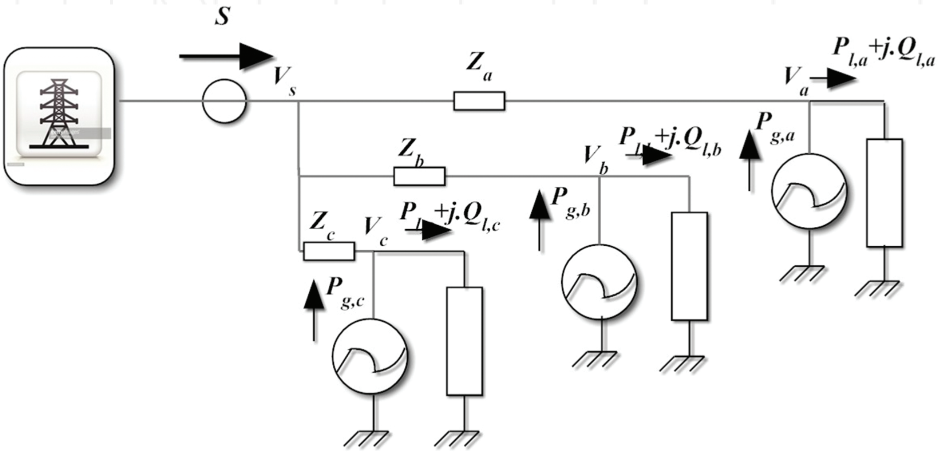

Figure 1. Distribution network equivalent, with renewable energy sources.

2.1.1. Voltage rise

Voltage rise due to high penetration of renewable energy sources is the main power quality issue in future distribution network. In high generation mode, as the load is usually in off-peak mode, there is an unbalancing between generation and load. This unbalancing can cause voltages to rise. To see this impact, let us have a close look at **Figure 1**. Based on this figure, the voltages magnitude for end of each phase can be written as [9]:

$$|V_a| = |V_s| + \frac{(P_{g,a} - P_{l,a}).R_a - Q_{l,a}.X_{l,a}}{|V_s|} \tag{1}$$

$$|V_b| = |V_s| + \frac{(P_{g,b} - P_{l,b}).R_b - Q_{l,b}.X_{l,b}}{|V_s|} \tag{2}$$

$$|V_c| = |V_s| + \frac{(P_{g,c} - P_{l,c}).R_c - Q_{l,c}.X_{l,c}}{|V_s|} \tag{3}$$

where

P_{ga}, P_{gb} and P_{gc} are the injected active power in each phase,

P_{la}, P_{lb} and P_{lc} are the consumed active power in each phase,

Q_{la}, Q_{lb} and Q_{lc} are the reactive power in each phase,

R_a, R_b and R_c are the line resistance of each phase,

X_a, X_b and X_c are the line reactance of each phase.

It can be seen that when a phase source active power is more than the load in that phase, the phase voltage will increase. If this unbalancing is considerably high, a stationary limit can be violated which is not acceptable by regulations and standards.

2.1.2. Voltage unbalancing

Voltage unbalancing is happening when there are differences between the three phase voltage magnitudes and/or angles (not separated by 120°). Based on Eqs. (1)–(3), as the loading and generation of a phase changes with respect to other phases, the magnitudes or angles of V_a, V_b and V_c will be unbalanced. Therefore, it can be seen that the voltage unbalancing is a common power quality issue in distribution network. The voltage unbalancing is usually measured by voltage unbalancing factor (VUF) as in Eq. (4) [10].

$$\%VUF = \frac{|V_-|}{|V_+|} \times 100 \tag{4}$$

where V_- and V_+ are the negative and positive sequence voltage components which can be calculated as follow:

$$V_- = \frac{V_a + a.V_b + a^2.V_c}{3} \tag{5}$$

$$V_+ = \frac{V_a + a^2.V_b + a.V_c}{3} \tag{6}$$

where

$$a = 1 < 120 \, \text{and} \, a^2 = 1 < 240.$$

Based on national standards, usually up to a maximum VUF of 2% is accepted in distribution network [11].

2.1.3. Harmonic

As most renewable energy sources are connected through power electronic converter to the distribution network, they usually inject harmonics to the network. Total Harmonic Distortion (THD) is usually considered as the harmonic index which normally need to be <5% based on standards [12].

2.1.4. Frequency variation

Frequency deviation can also result from unbalancing between load and generation. During peak generation period, when generation is more than load, the frequency may rise. Additionally, during peak load period, the load is higher than generation which may cause the frequency to drop.

2.1.5. Loading constraint violation

Based on **Figure 1**, the load of each phase and power transformer can be written as follows:

$$|S_a| = \sqrt{(P_{l,a} - P_{g,a})^2 + Q_{l,a}^2} \tag{7}$$

$$|S_b| = \sqrt{(P_{l,b} - P_{g,b})^2 + Q_{l,b}^2} \tag{8}$$

$$|S_c| = \sqrt{(P_{l,c} - P_{g,c})^2 + Q_{l,c}^2} \tag{9}$$

$$S = S_a + S_b + S_c \tag{10}$$

where S_a, S_b and S_c are the apparent power of each phase and S is the apparent power of power transformer.

Based on these equations, it can be seen that the loading of lines and power transformer depends on the difference between generation and load in each phase. If this difference is high, it can violate some of the facilities' thermal limit.

In this chapter, this issue is considered as one of the requirements for distribution network operation, which need to be dealt with using available resources in the network.

2.2. Coordinating network resources based on network requirements

Future distribution networks will include a lot of controllable resources which can be used and coordinated based on different network requirements. This section lists some of the resources, which can be utilised based on network requirements.

2.2.1. Source active power

Injecting surplus active power to the grid by renewable energy source is the main cause of power quality issues. Therefore, one way to deal with these issues is to control the injecting power. For instance, Refs. [7, 9, 13] use active power curtailment as a robust control approach to deal with voltage rise issue.

2.2.2. Source reactive power

Another resource which can be used to deal with power quality issues in distribution network is reactive power contribution of renewable energy sources. This strategy is usually used to deal with voltage fluctuation in distribution network. References [14–16] use reactive power control in distribution network to deal with voltage rise.

2.2.3. Controllable load

To deal with the unbalance between load and generation, smart controllable loads such as air-conditioner or washing machine are suitable options which can be utilised to deal with power quality issues as well [17]. These resources can be used for both voltage and loading support in network. References [13, 16] use these resources to prevent overvoltages in distribution network.

2.2.4. Energy storage system (ESS)

ESS has an important role in developing future smart grid [18] which appears in several types such as flywheel, super capacitor, compressed gas and battery. Battery is the most popular ESS in distribution network which can be considered as the suitable option for customers or utilities application based on network requirements. This facility can be charged during high generation period, while discharging during peak load period. Therefore, it can easily reduce the unbalancing between generation and loading, while dealing with network issues.

Based on the versatility and vital role of batteries in future distribution grids, storage has been included in this chapter as part of the strategy and application for load and renewable energy management, while considering its role in resolving network quality issues for future distribution systems.

3. Distributed control management and its application in distribution network

Distributed control is an effective management approach for future smart grids with distributed resources. This approach has been applied in various literatures in recent years. There are two comprehensive review papers which study the application of distributed control in power systems. Reference [19] presented different types of distributed multi-agent systems and their applications in power systems. In Ref. [20], the applications of distributed control in micro-grids are studied which includes; primary control, voltage coordination, economic dispatch and frequency control. In this study, distributed control are categorised based on problem formulisation into three main categories [20]:

- Predictive control-based approach,
- Agent-based approach,
- Consensus-based approach.

Consensus-based approach is a new distributed control approach which aims to have an equal proportionality-based converging sate for the resources. In Ref. [2], this approach is used to deal with network loading, while coordinating storage units in a fair way. Reference [7] adapted an overvoltage control approach based on this algorithm which uses fair battery charging to prevent voltage rise in low voltage network.

Consensus algorithm also applied in recent studies to provide optimal utilisation of resources as well. In [8], a new distributed updating approach is used to utilise batteries in an efficient way in micro-grid. A new distributed optimal control approach is proposed in [21] which manages multiple generators based on consensus algorithm. It can be seen that the consensus-based distributed approach has attracted a lot of studies in recent years. This book chapter includes the use of this algorithm as the backbone of distributed management of resources in distribution network. The model for this algorithm is as follow:

In consensus algorithm, network is modelled with graph G having N vertices. The graph is shown by $G(V, E)$ where V is the set of vertices and E is the set of edges. For this graph, $(i,\ j) \in E$ if node i can receive information from node j. This communication link is shown by c_{ij} in which the value of 1 for this parameter means there is a communication link and 0 means no communication. Additionally, neighbours of node i are those nodes which send information to node i which are shown by set of $N_i = \{ j \in V,\ (i,\ j) \in E \}$ [6].

In consensus algorithm, a parameter named as information state is defined for each resource. Based on this algorithm, the information state of each resource is a function of information state of its neighbours which can be shown as in Eq. (11) [6].

$$\varepsilon_i[t] = \sum_{j \in N_i} d_{ij} \varepsilon_j[t] \tag{11}$$

where

$\varepsilon_i(t)$ is the information state of ith resource and;

$$d_{ij} = \frac{c_{ji}}{\sum_{k \in N_i} c_{ki}} \tag{12}$$

4. Distributed management of energy resources based on specific network requirement

As noted before, distributed management approach has been applied in variety of power system applications. In this section, the aim was to apply distributed control approach for specific application, which is distributed loading management in distribution network. Battery as an ESS with its associated inverter is considered as the main resource which can be used for this purpose.

If there is only one single ESS in distribution network, there is no need to apply any coordination strategy. However, future distribution network may include high number of ESSs; therefore, a coordination strategy is needed to coordinate these units based on specific objective function.

The proposed control structure for distribution network which coordinates multiple ESSs is shown in **Figure 2**. To manage multiple ESSs in a distributed way, a communication link is assumed between neighbouring ESSs. Additionally, there is a control agent named as the leader which monitors network loading and initiates the ESS coordination whenever it is needed.

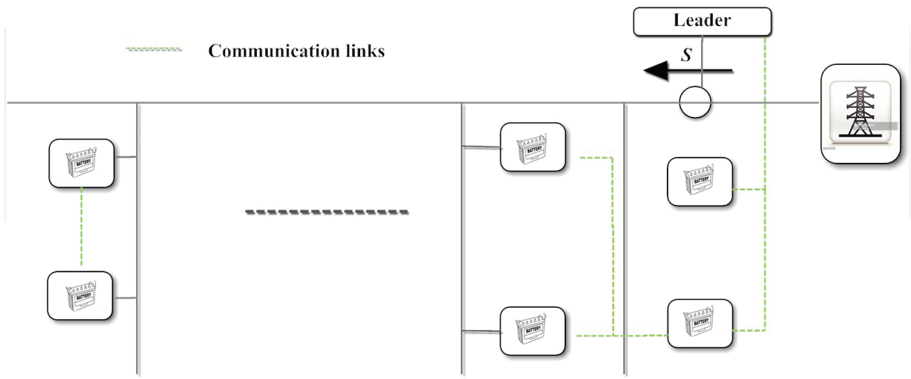

Figure 2. Distributed control structure for distribution network.

To coordinate the ESSs for loading management, three operating control modes are considered for the network. These network control modes are shown in **Figure 3**, which there are four limits that determine the network control modes. If the network loading is within desirable range ($S_d^{gen.}$ and $S_d^{cons.}$), the network is in normal condition. Therefore, there is no need for ESSs' coordination based on network requirements and they can operate based on other objectives. If network loading violates $S_c^{gen.}$, the network goes to the high generation control mode. In this control mode, ESSs should be coordinated to charge and reduce the network loading. Additionally, if the network loading violates $S_c^{cons.}$, the network goes to the high consumption mode which means that the ESSs should be coordinated to discharge and reduce the network loading.

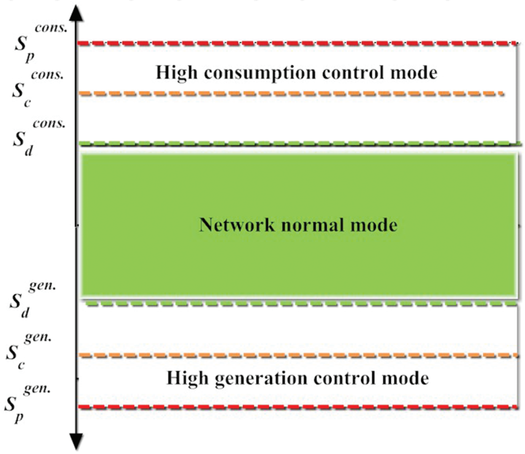

Figure 3. Network control modes based on predefined limits.

Based on consensus algorithm in this section, two distributed management approaches are proposed to coordinate multiple ESSs for loading management. Each distributed approach follows a specific objective function.

To find these objective functions, the ESS's owner interest is considered. If the ESS owners are customers, their preference is assumed to have a fair contribution in loading management. In other words, all customers prefer to have a fair sharing in loading management. However, for utility owned EES, the aims normally were to maximise the ESSs' utilisation of these devices. Therefore, it can be said that a proper coordination should be considered for each of these objectives. The details of the two distributed control approaches which consider each of these objectives to coordinate multiple ESSs are as follow:

4.1. Network loading management using fair sharing of multiple ESSs

In this case, the objective function includes two main parts [2]. To keep the network loading within acceptable range, the first objective was defined by keeping the network loading between critical limits:

$$S_c^{gen.} \leq S \leq S_c^{cons.} \tag{13}$$

Additionally, to have a fair sharing among multiple ESSs, the second objective was defined by having the following ratio

$$\frac{P_1}{P_1^{\max.}} = \frac{P_2}{P_2^{\max.}} = \ldots = \frac{P_n}{P_n^{\max.}} \tag{14}$$

where

$P_1^{\max.}$ is the maximum active power available ith ESS which depends on its state-of-charge (SOC). The objective can be also rewritten as follow:

$$\frac{P_1}{SOC_1} = \frac{P_2}{SOC_2} = \ldots = \frac{P_n}{SOC_n} \tag{15}$$

To achieve the noted objectives, the control structure of the leader, shown in **Figure 4**, will be used. In other words, as soon as the critical limits for generation or consumption are violated, the leader starts to update its information state as given in Eqs. (16) and (17).

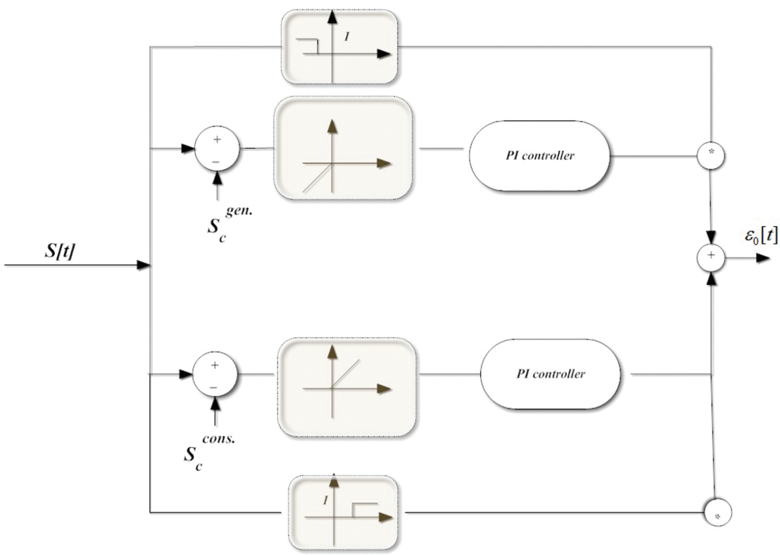

Figure 4. Leader control structure for ESS fair contribution.

$$\varepsilon_0[t] = \varepsilon_0[t - t_s] + k.(S[t] - S_c^{gen.}) \tag{16}$$

$$\varepsilon_0[t] = \varepsilon_0[t - t_s] + k.(S[t] - S_c^{cons.}) \tag{17}$$

Once the leader initiates the control, the ESSs will update their information state based on consensus algorithm, as given in Eq. (18).

$$\varepsilon_i[t] = \sum_{j \in N_i} d_{ij} \varepsilon_j[t] \tag{18}$$

Based on the calculated ESS state information, the reference for ESS active power will be updated as in Eq. (19).

$$P_i[t] = \varepsilon_i[t].P_i^{\max.} \tag{19}$$

The flowchart of this distributed loading control management is shown in **Figure 5**.

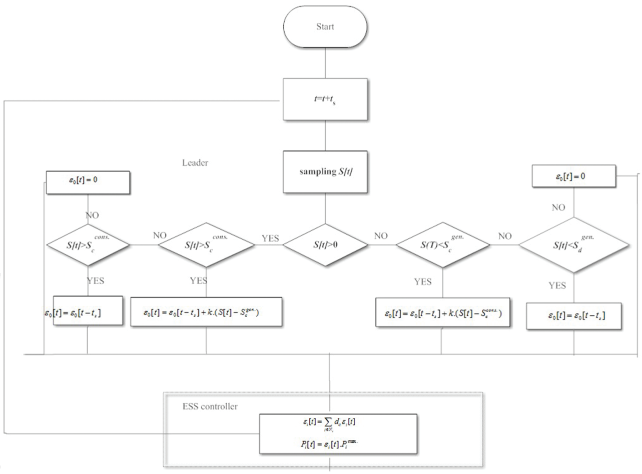

Figure 5. Distributed control structure for fair sharing of multiple ESSs.

4.2. Network loading management using optimal utilisation of multiple ESSs

In this case, the interest of utility is considered in managing multiple ESSs. In other words, the aim was to use ESSs for loading management while the utilisation rate and efficiency of the batteries are maximised. To achieve such an objective, the cost function given in Eq. (20) is used for each storage unit [22].

$$C_i(|P_i|) = \eta_i.|P_i| = a_i.|P_i| - b_i.|P_i|^2 \tag{20}$$

where

η_i is the efficiency of ESS in charging and discharging mode (it is assumed to be the same in both mode).

a_i and b_i are the efficiency coefficient of ESS.

In this case, the goal was to maximise this cost function while reduce loading to less than the critical limits. For instance, in high generation control mode, the cost function can be written as follows:

$$\begin{aligned} &Max \sum_{i=1}^{N_s} C_i(|P_i|) \\ &\sum_{i=1}^{n} |P_i| = |S - S_c^{gen.}| \\ &P_i^{\min.} \le P_i \le P_i^{\max.} \end{aligned} \tag{21}$$

Note that the same cost function can be used for high loading control mode, and only the equality constraint will change.

Based on central optimisation approach, the optimal point of incremental cost is as follows

$$\varepsilon^* = \frac{(\sum_{i=1}^{n} \frac{a_i}{2b_i} - |S - S_c^{gen.}|)}{\sum_{i=1}^{n} \frac{1}{2b_i}} \tag{22}$$

To converge the optimal point and maximise cost function in Eq. (21), the iterative updating approach of the following equations is used [8]:

$$\varepsilon_i[t + t_s] = \sum_{j \in N_i} d_{ij}.\varepsilon_j[t] + \alpha.P_{l,i}(t) \tag{23}$$

$$|P_i[t + t_s]| = (\frac{-\varepsilon_i(t + t_s) + a_i}{2.b_i}) \tag{24}$$

$$P'_{l,i}[t+t_s] = P_{l,i}[t] + (|P_i(t+t_s]| - |P_i(t]|) \tag{25}$$

$$P_{l,i}[t+t_s] = (\sum_{j\in N_i} d_{ij}.P'_{l,j}[t]) \tag{26}$$

$$flag_i[t] = flag_{i-1}[t-t_s] \tag{27}$$

$$P_i[t] = flag_i[t].|P_i[t]| \tag{28}$$

If this iterative process is initiated by leader using Eqs. (29) and (30) when the critical limit is violated;

$$flag_0[t] = -1 \tag{29}$$

$$P_{l,i}(t) = \begin{cases} S - S_c^{gen.} & i = 1 \\ 0 & i \neq 1 \end{cases} \tag{30}$$

Based on Ref. [8], the Eqs. (23) and (24) converge to the following:

$$\varepsilon[\infty] = [\varepsilon^* \quad \varepsilon^* \quad \ldots \quad \varepsilon^*]_n = \varepsilon^*.1_n \tag{31}$$

$$\sum_{i=1}^{n} |P_{l,i}(0)| = -\sum_{i=1}^{n} \frac{1}{2.b_i}.\varepsilon^* + \sum_{i=1}^{n} \frac{a_i}{2b_i} \tag{32}$$

Therefore, it can be seen that the incremental cost converge to the noted optimal point, as given in Eq. (33)

$$\varepsilon^* = \frac{(\sum_{i=1}^{n} \frac{a_i}{2b_i} - |S - S_c^{gen.}|)}{\sum_{i=1}^{n} \frac{1}{2b_i}} \tag{33}$$

The flowchart of this distributed loading control management approach is shown in **Figure 6**.

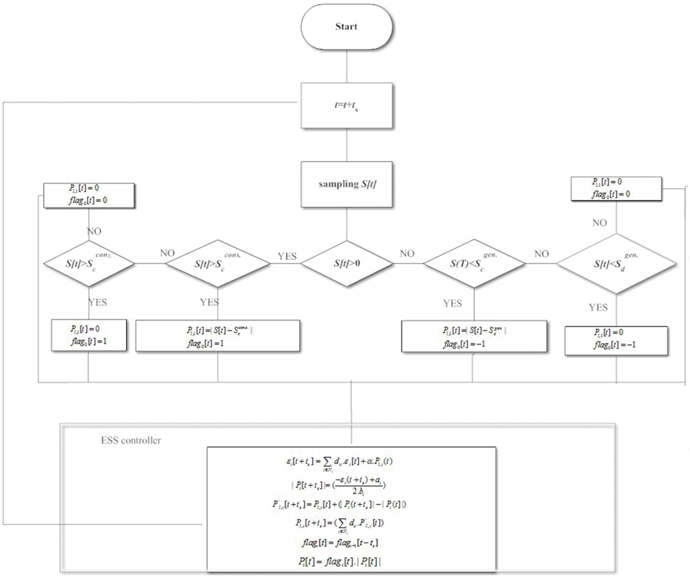

Figure 6. Distributed control structure for optimal utilisation of multiple ESSs.

5. Case studies

In this section, IEEE 33-bus distribution system is used to assess the performance of the distributed loading management approaches [23]. The details of ESSs are shown in **Table 1**. All the buses assumed to have their peak generation the same as their peak load. The aim of this section was to coordinate multiple ESSs to manage the loading of this network within −3000 to 3000 kVA as given in **Table 2**. To assess the performance of this approach in different network modes, the loading and generation profiles for each bus given in **Figure 7** are considered. The profiles are based on maximum loading and generation at each bus. MATLAB platform is used to implement the proposed approaches in the following case studies.

ESS	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Location (bus)	2	8	12	15	20	27	30	33
Rating (kW)	150	160	120	180	100	140	150	140
a_i	.91	.9	.89	.9	.9	.92	.9	.9
b_i	.09	.05	.12	.12	.13	.09	.08	.1

Table 1. ESSs parameters.

Parameter	Power (kVA)
$S_p^{cons.}$	3200
$S_c^{cons.}$	3000
$S_d^{cons.}$	2800
$S_d^{gen.}$	−2800
$S_c^{gen.}$	−3000
$S_p^{gen.}$	−3200

Table 2. Loading limits in the proposed approach.

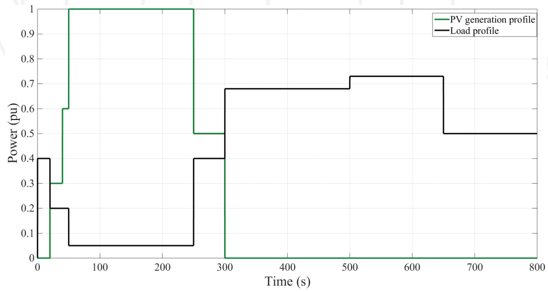

Figure 7. Load and generation profiles at each bus.

5.1. Case 1

The aim of this case study was to coordinate multiple ESSs in a fair way, while managing the network loading. The results for distributed loading management using this approach are shown in **Figure 8**. As it can be seen, the system goes to the high generation control mode at t = 50 s and multiple ESSs reduce the power injected to the upper level grid $<S_c^{gen.}$. The contribution of each ESS at steady state is listed in **Table 3**, which follows the fair sharing objective as follow:

$$\frac{P_1}{P_1^{\max.}} = \frac{P_2}{P_2^{\max.}} = \ldots = \frac{P_8}{P_8^{\max.}} = -0.344$$

The same scenario is happening at t = 500 s in which the ESSs goes to the high consumption control mode, with ESS contribution for loading management in a fair way as given in following:

$$\frac{P_1}{P_1^{\max.}} = \frac{P_2}{P_2^{\max.}} = \ldots = \frac{P_8}{P_8^{\max.}} = 0.158 \tag{36}$$

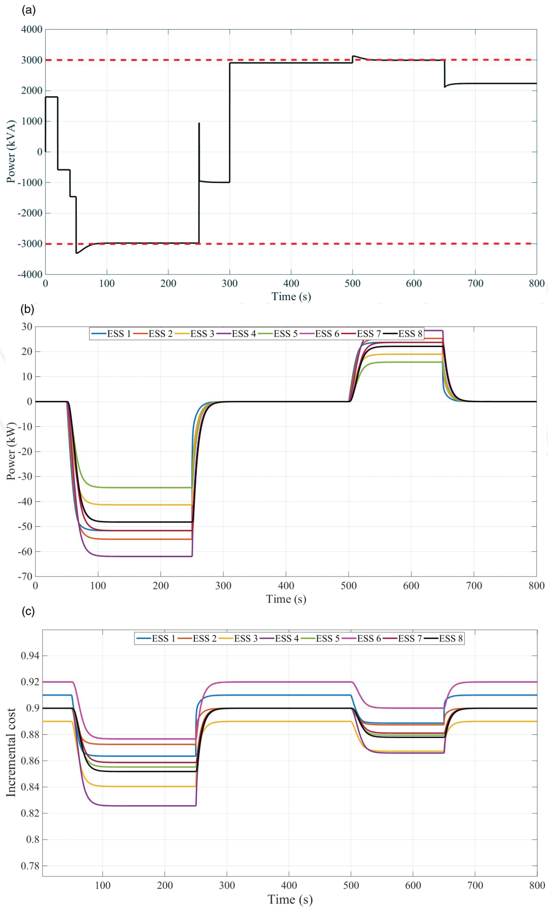

Figure 8. Results for fair sharing among ESSs (a) network loading, (b) ESS contribution, (c) incremental cost.

ESS	1	2	3	4	5	6	7	8	Total
0–50 s	0	0	0	0	0	0	0	0	0
50–250 s	0	0	0	0	0	0	0	0	0
50–250 s	−51.631	−55.073	−41.304	−61.957	−34.420	−48.188	−51.631	−48.188	−392.36
250–500 s	0	0	0	0	0	0	0	0	0
500–650 s	23.698	25.278	18.958	28.437	15.798	22.118	23.698	22.118	157.93
650–800 s	0	0	0	0	0	0	0	0	0

Table 3. ESSs power contributions for loading management.

5.2. Case 2

In this case, the aim was to coordinate multiple ESSs, while optimising their utilisation rate and maximise the cost function in Eq. (21). The results for this case are shown in **Figure 9**. The ESSs' contributions for each time step are listed in **Table 4**. It can be seen that the ESSs with lower cost coefficients contribute more in loading management. Additionally, the total ESSs contribution in each time step is less than the previous case which shows the advantage in promising features of this optimal approach.

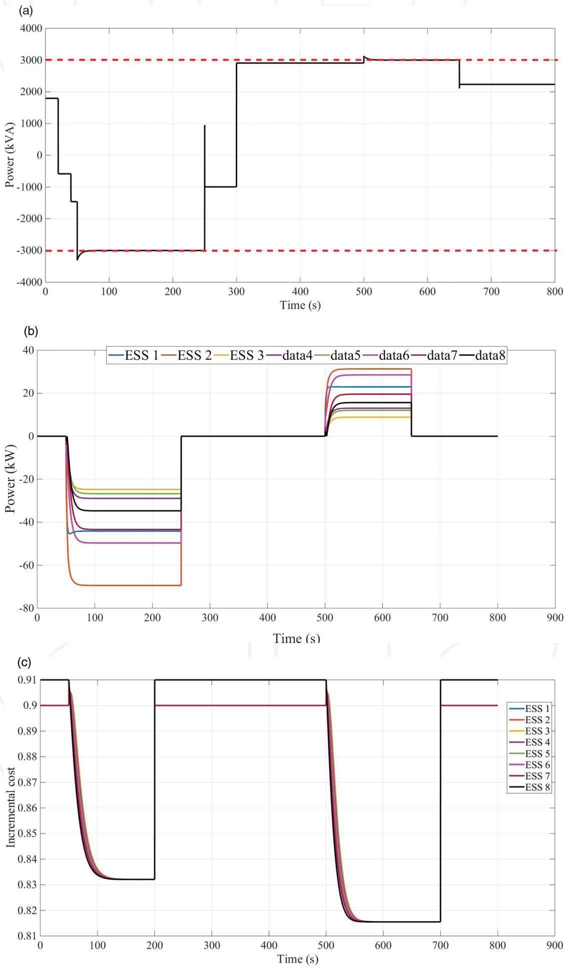

Figure 9. Results for optimal ESSs coordination, (a) network loading, (b) ESS contribution, (c) incremental cost.

ESS	1	2	3	4	5	6	7	8	Total
0–50 s	0	0	0	0	0	0	0	0	0
50–250 s	0	0	0	0	0	0	0	0	0
50–250 s	−44.12	−69.41	−24.75	−28.92	−26.70	−49.67	−43.38	−34.70	−321.65
250–500 s	0	0	0	0	0	0	0	0	0
500–650 s	22.96	31.33	8.89	13.05	12.05	28.52	19.58	15.67	152.05
650–800 s	0	0	0	0	0	0	0	0	0

Table 4. ESSs power contributions for loading management.

5.3. Case 3

Finally, in this case, the impact of communication drop is studied on the distributed loading management approaches. To model this impact, it is assumed that the communication links between ESS 4 and 5 are unavailable during t = 450–600 s as given in Eq. (34).

$$c_{45} = c_{54} = \begin{cases} 1 & t < 450 \quad t > 600 \\ 0 & 450 \leq t \leq 600 \end{cases} \tag{34}$$

The results for both scenarios are provided as follow. For the first case in which ESSs are coordinate in a fair way as shown in **Figure 10**, it can be seen that as soon as the loading passes the critical limit, ESSs 1, 2, 3 and 4 start to coordinate and reduce the loading to the allowable range. However, ESSs 5, 6, 7 and 8 cannot be coordinated due to the communication loss between ESSs 4 and 5. The ratio of contribution of each ESS is as follow:

$$\frac{P_1}{P_1^{\max.}} = \frac{P_2}{P_2^{\max.}} = \frac{P_3}{P_3^{\max.}} = \frac{P_4}{P_4^{\max.}} = 0.251$$

$$\frac{P_5}{P_5^{\max.}} = \frac{P_6}{P_6^{\max.}} = \frac{P_7}{P_7^{\max.}} = \frac{P_8}{P_8^{\max.}} = 0$$

As soon as the communication link is available at t = 600 s, ESSs 5, 6, 7 and 8 will start to contribute to loading management and their contribution converge to 0.251. So, comparing with the case with no communication drop, it can be seen that the communication drop causes this approach to use more resources than required (contributing ratio of 0.251 instead of 0.158). However, the robustness of the approach to keep the loading within the allowable range has still been achieved.

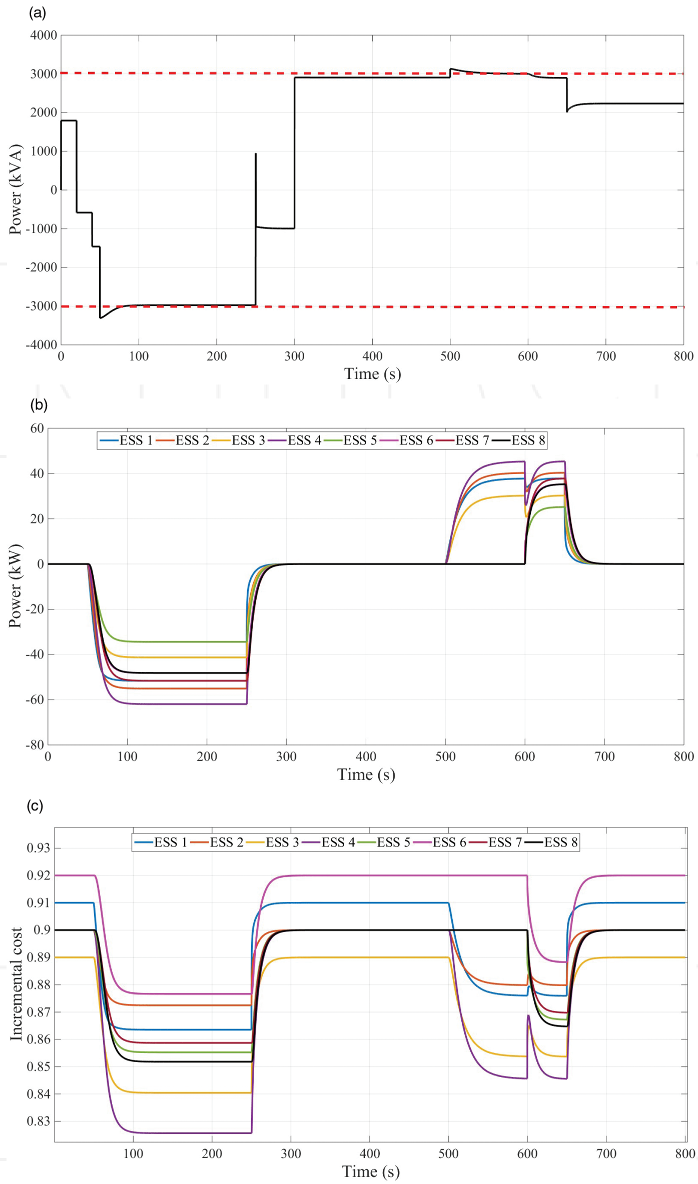

Figure 10. Impact of communication drop on fair sharing among ESSs (a) network loading, (b) ESS contribution, (c) incremental cost.

In the last case, the impact of communication drop was studied on the second approach. The same scenario is simulated for this case as well. The results are provided in **Figure 11**. Again, as there is no communication between ESS 4 and 5, only ESS 1, 2, 3 and 4 contributes in loading management. As soon as communication drop failure is repaired, ESSs 5, 6, 7 and 8 start to contribute in loading management. As the results show, all the ESSs have the same contribution compared with no communication drop case. Therefore, it can be said that communication drop may limit the resources while optimal operation is achieved all the time, in this case.

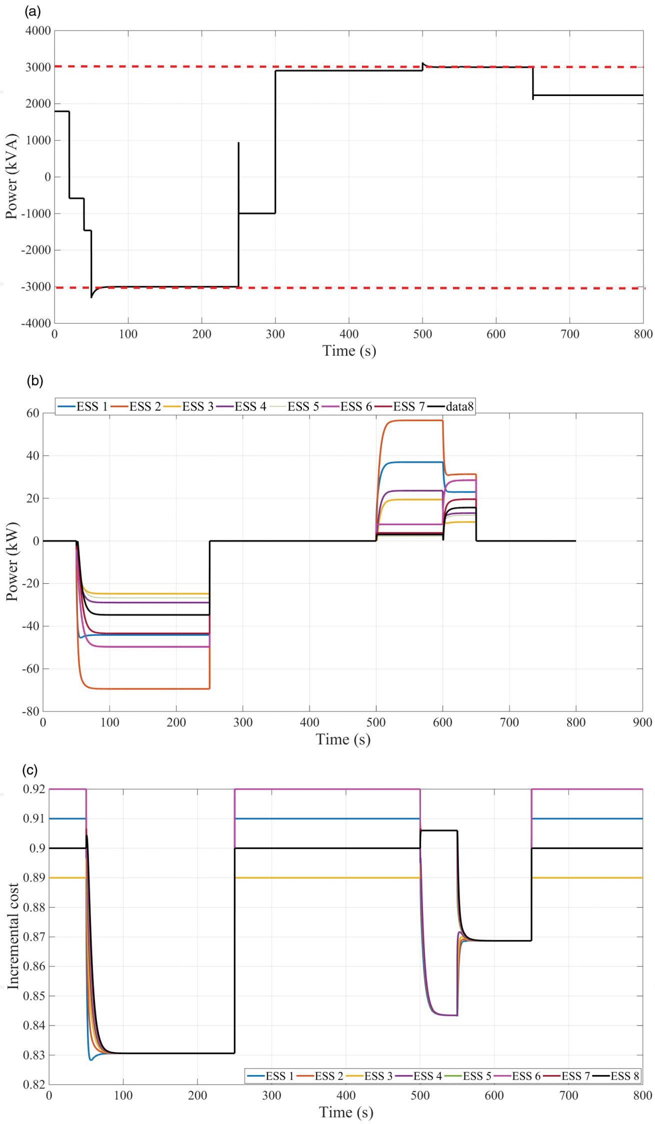

Figure 11. Impact of communication drop on optimal ESSs coordination, (a) network loading, (b) ESS contribution, (c) incremental cost.

6. Conclusions

Future distribution networks with high utilisation of renewable energy resources can encounter network operating problems. Network voltage and loading issues are usually listed as the main network concerns which need to be addressed properly. As discussed and shown in this chapter, utilities and/or customers' storage resources can be used to resolve these issues. As part of this approach, distributed control method with consensus algorithm was presented in this book chapter. Application and results were also provided to support this technique over the existing methods, as a promising alternative to achieve accurate and efficient solution. Finally, the application of distributed control management strategy that coordinates multiple ESSs to deal with distribution network overloading was discussed in details. In this approach, both utility and customer interests were considered as part of a robust technique for loading management approach in future distribution network.

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