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Published in:
Energies

DOI (link to publication from Publisher):
10.3390/en10030293

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Mokhtari, G., Nourbakhsh, G., Anvari-Moghaddam, A., Ghasemi, N., & Saberian, A. (2017). Optimal Cooperative Management of Energy Storage Systems to Deal with Over- and Under-Voltages. *Energies*, *10*(3), 1-17. Article 293. https://doi.org/10.3390/en10030293

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Optimal Cooperative Management of Energy Storage Systems to Deal with Over- and Under-Voltages

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Academic Editor: William Holderbaum
Received: 4 January 2017; Accepted: 28 February 2017; Published: 2 March 2017

Abstract: This paper presents an optimal cooperative voltage control approach, which coordinates storage units in a distribution network. This technique is developed for storage systems' active power management with a local strategy to provide robust voltage control and a distributed strategy to deliver optimal storage utilization. Accordingly, three control criteria based on predefined node voltage limits are used for network operation including normal, over-voltage, and under-voltage control modes. The contribution of storage units for voltage support is determined using the control modes and the coordination strategies proposed in this paper. This technique is evaluated in two case studies to assess its capability.

Keywords: storage; optimal control; over-voltage; under-voltage; cooperative control

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1. Introduction

Due to their significant benefit for customers and utilities, renewable energy resources are increasingly utilized in power systems around the world. However, the traditional distribution networks are not designed to accommodate renewable energy resources [1]. As such, power quality issues gradually are becoming the main concern for future grids with high utilization of these sources [2]. With the high integration of renewable energy generation in distribution networks, voltage violations may occur during high generation and peak load periods, as these events do not happen at the same time [3]. Normally, over-voltage occurs during peak generation times, while under-voltage is experienced during peak load demand periods. National standards usually specify that all node voltages in a network must be kept within a range (usually between 0.94 and 1.06 per unit (pu)). Violation of these limits can cause problems for sensitive consuming and generating facilities [4]. Hence, both over- and under-voltage issues can create major obstacles for penetration of renewable energy generation in future distribution networks [5]. Normally, the unbalance between the load and generation at any period is the main cause of the issues [6].

Several approaches are proposed in literature to mitigate voltage issues in distribution networks. These methods can be categorized into two broad classes. The first class uses customer resources—such as renewable energy source active power [7], renewable energy source reactive power [8], and smart loads [9]—to avoid over- and under-voltages, while the second class uses utility-owned resources such as a distribution static synchronous compensator (D-STATCOM) [10] and on-load tap-changer (OLTC) [11] to deal with the same issues.

Storage units have shown to have attractive peripheral utilization features, including reduction in generation/load mismatch [12], frequency regulation [13], and peak shaving [14]. In general, the main applications of storage units in power systems can be divided into two categories. In the first category, the storage active or reactive power are used to provide power quality improvement in the distribution network [15]. For instance, Reference [2] uses storage active and reactive power for loading and voltage support in the distribution network. In another reference, storage active power is used to provide frequency control in the distribution network [13]. Peak shaving and load leveling are other applications of storage units in which storage units charging and discharging will be used to reduce the peak generation and peak demand [16]. In the second application, the storage units are utilized to improve self-consumption in residential sectors [17].

In distribution networks, including both medium- and low-voltage feeders, storage units usually are used for two main purposes. Customers as the main stakeholders use storage units to improve their self-consumption and to reduce their electricity bill. Normally in this case, the storage units are managed by customers, based on their goals. However, a storage coordination strategy is required when a network is faced with power quality issues.

Supervisory control coordination is not a practical strategy in a distribution network due to its complexity and reliability issues [12]. However, combined local and distributed control coordination approaches can provide promising features for future distribution networks with high utilization of energy resources [2]. A combined local and distributed control strategy is proposed in this paper to coordinate multiple storage units dealing with over- and under-voltage issues in distribution networks. The local control approach uses point of common coupling (PCC) bus voltage as a reference to control storage units' active power in order to avoid violating voltage limits. Simultaneously, a distributed control strategy is used as a supplementary scheme to provide optimal utilization of storage units. It is worth nothing that we consider batteries as the storage units due to their common utilization in distribution networks.

2. Proposed Approach

In order to optimally coordinate and manage the operation of energy storage units in a typical distribution network, it is crucial to consider the aims and objectives of the asset owners. Given a normal operating condition (i.e., in the absence of network voltage and/or loading issues), the storage units are mainly dispatched in a way to improve the self-consumption and reduce the electricity bills if they are owned by "customers". In this case, normally, a local control architecture is needed to meet the noted objectives. However, with utility as the storage owner, the aim will be to deal with the network problems in an efficient way, which in turn necessitates a coordinated control architecture. Therefore, efficient control of storage units greatly depends on the system's objectives, related security/technical constraints, and operating modes.

This paper proposes an efficient cooperative control approach (which includes both local and distributed control approaches) to deal with over- and under-voltage issues in distribution network. As can be seen in Figure 1, the local control approach uses the storage units at PCC bus voltages to determine the contribution of these units for a robust voltage control, while the distributed control approach determines the optimal contribution of storage units for voltage support.

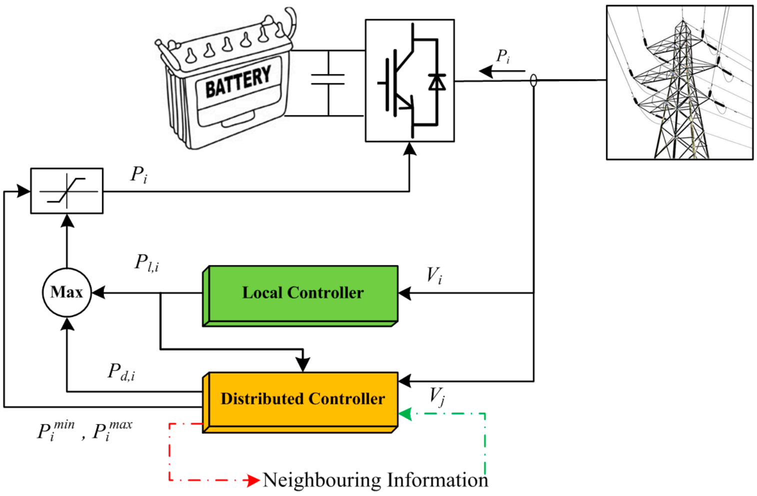


Figure 1. Proposed control structure for storage unit.

2.1. Local Voltage Control Strategy

The local control approach uses the storage units at PCC bus voltages to determine the contribution of these units for a robust voltage control. In order to determine the triggering criteria for the local controllers, three control modes are defined for network operation, as given in Figure 2.

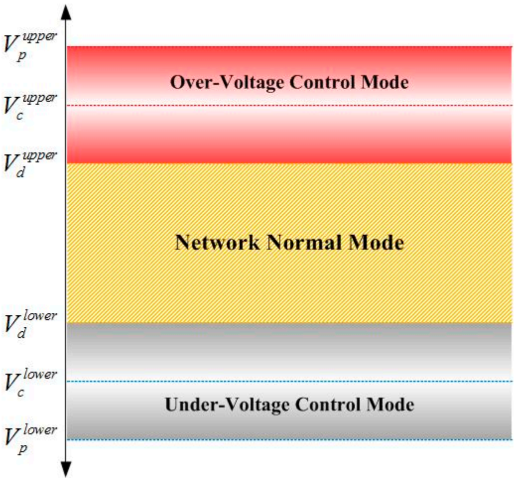


Figure 2. Network control modes based on voltage limits.

If the voltages of all storage units are in the desirable range (between V_d^{lower} and V_d^{upper}), the network control mode is normal. Therefore, storage units can be used for other purposes such as power buffering and so on. The second control mode engages when the voltage at any of the storage unit buses exceeds V_c^{upper}. In this case, storage units go to the over-voltage control mode and they start to collaborate with each other in coordinating their charging rate to achieve robust and efficient over-voltage prevention. This coordination continues until all the bus voltages go to the desirable range and the network goes to the normal mode.

Finally, under-voltage control mode is treated similar to the over-voltage control mode, where V_c^{lower} and V_d^{lower} determine the start and stop of this control mode. It should be noted that the aim of over- or under-voltage control is to avoid any bus violating the permissible limits (i.e., V_p^{lower} and V_p^{upper}).

Each storage unit is supported by both local and distributed controllers. As soon as the voltage at a storage unit bus violates V_c^{lower} or V_c^{upper}, the local controller updates its reference power, as in (1).

$$P_{l,i}[k] = \begin{cases} m_{i,o} \cdot (V_i[k] - V_c^{upper}) & V_i[k] > V_c^{upper} \\ 0 \quad V_c^{lower} < V_i[k] < V_c^{upper} \\ -m_{i,u} \cdot (V_i[k] - V_c^{lower}) & V_i[k] < V_c^{lower} \end{cases} \tag{1}$$

where $P_{l,i}$ is the local contribution of storage unit, and $m_{i,o}$ and $m_{i,u}$ are the droop coefficients. As storage units should start to charge or discharge at critical limits and use their maximum capability in permissible limit, the droop coefficient is proposed as in Equations (2) and (3).

$$m_{i,o} = |\frac{P_i^{ava.}}{V_p^{upper} - V_c^{upper}}| \tag{2}$$

$$m_{i,u} = |\frac{P_i^{ava.}}{V_p^{lower} - V_c^{lower}}| \tag{3}$$

where $P_i^{ava.}$ is the maximum available power in storage unit *i*.

Additionally, to show that the network mode is changed, a local voltage control flag is used, as given in (4).

$$Lflag[k] = \begin{cases} 1 & V_i[k] > V_c^{upper} \\ 0 & V_c^{lower} < V_i[k] < V_c^{upper} \\ -1 & V_i[k] < V_c^{lower} \end{cases} \tag{4}$$

Based on this control structure, as soon as the voltage at any storage bus passes the critical limit, the storage unit starts to charge or discharge to deal with over- or under-voltage issues. Although this control can provide a robust over/under voltage control, it may not follow the optimal storage unit utilization. Therefore, a distributed control approach is used to guarantee the optimal utilization of storage units. Details of this control strategy are described in the following section.

2.2. Cooperative Voltage Control Strategy

A consensus algorithm is a distributed control that provides fair sharing among resources in a network. In this algorithm, the resources in a network are represented by a graph (*V*, *E*), where *V* models graph vertices and *E* models the graph edges, and pair (*i*, *j*) is member of *E* if there is an edge between vertices *j* and *i*. An example of this graph model is shown in Figure 3.

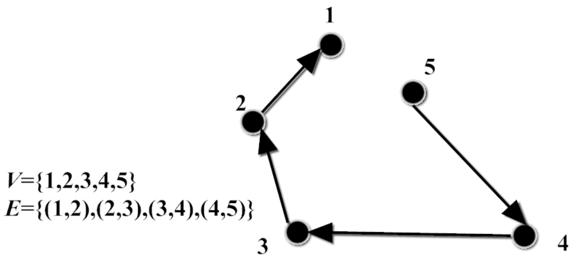


Figure 3. Graph model of resources.

For each vertex, the set N_i shows its neighbors, as given in (5).

$$N_i = \{j \in v | (i,j) \in E\} \tag{5}$$

Based on this technique, for each resource in node i, a parameter named information state ($\lambda_i(t)$) is defined, which will be updated as in (6) to achieve a specific control objective [1].

$$\dot{\lambda}_i(t) = \sum_{j \in N_i} d_{ij} \lambda_j(t) \tag{6}$$

where d_{ij} is a coefficient defined as in Equation (7) [18].

$$d_{ij} = \frac{c_{ji}}{\sum\limits_{k \in N_i} c_{ki}} \tag{7}$$

where c_{ij} models the communication link between resource i and j. In a discrete time domain, (7) can be shown in matrix format as given in (8).

$$\lambda[k+1] = D \cdot \lambda[k] \tag{8}$$

This algorithm has been applied in applications which require fair sharing among resources [19]. For example, in [2], this approach is used to provide fair sharing of active power among storage units to perform load management in a power system; in [20], this approach is adopted for load sharing among photovoltaic (PV)-storage system of a low-voltage network. In recent literature, this approach is also used to provide optimal utilization of resources [21]. Based on the noted literatures, the proposed distributed control structure for a storage unit is implemented in this paper, as shown in Figure 4.

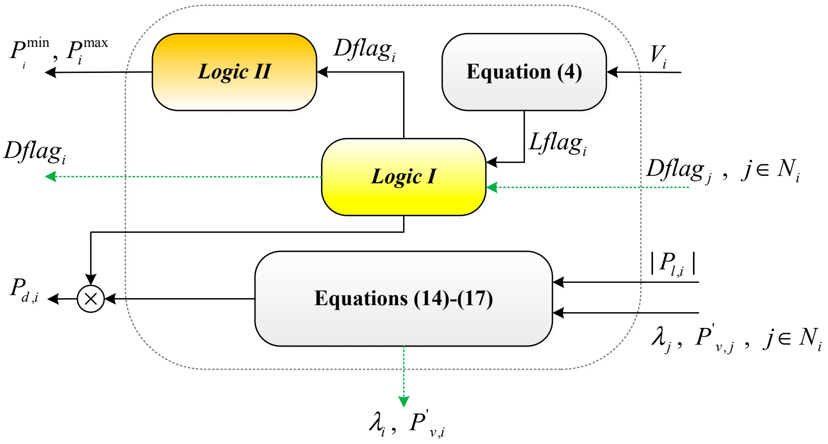


Figure 4. Proposed structure for distributed controller.

The maximum and minimum power of a storage unit depends on the control mode of the network. *Lflag* is a local index of a network control mode. However, to extend the network mode to all storage units, $Dflag_i$ is also defined. A value is assigned to this index based on the following arguments: *Logic 1*: is followed to charge all storage units during over-voltages and discharge during under-voltages; *Logic 2*: is followed to determine the maximum and minimum of a storage unit's contributed power. These logics are formulated as follows:

Logic 1:

$$\begin{gathered} Dflag_i = 0 \text{ if } Lflag_i = 0 \text{ and all } \; Dflag_j = 0 \quad j \in N_i \\ Dflag_i = 1 \text{ if } Lflag_i = 1 \text{ or any of } \; Dflag_j = 1 \quad j \in N_i \\ Dflag_i = -1 \text{ if } Lflag_i = -1 \text{ or any of } \; Dflag_j = -1 \quad j \in N_i \end{gathered}$$

Logic 2:

$$\begin{array}{llll} P_i^{\min} = 0 & P_i^{\max} = P_i^{ava.} & if \quad Dflag_i & = 1 \\ P_i^{\min} = -P_i^{ava.} & P_i^{\max} = 0 & if \quad Dflag_i & = -1 \end{array}$$

In this paper, the aim is to use a consensus approach to provide an optimal utilization of storage units in voltage support. To achieve this objective, the utilization function of each storage unit is defined as (9).

$$C_i(|P_{d,i}|) = |P_{d,i}| \cdot \eta_i \tag{9}$$

where $P_{d,i}$ is the distributed contribution of storage unit, and η_i is the storage unit efficiency.

As noted in [21], the efficiency of the storage unit reduces when its power increases. Therefore, the storage efficiency depends on its output power, as given in (10).

$$\eta_i = a_i - b_i \cdot |P_{d,i}| \tag{10}$$

where a_i and b_i are coefficients that depend on the type of storage unit. These values can be different for charging or discharging. However, for the sake of simplicity, in this paper, fixed values are considered. So, the cost function for each storage unit can be shown as in (11).

$$C_i(|P_{d,i}|) = a_i \cdot |P_{d,i}| - b_i \cdot |P_{d,i}|^2 \tag{11}$$

In order to achieve an optimal utilization of energy storage units, the objective control function is defined as in (12).

$$\begin{array}{l} Max \sum\limits_{i=1}^{n} C_i(|P_{d,i}|) \\ s.t. \sum\limits_{i=1}^{n} |P_{d,i}| = \sum\limits_{i=1}^{n} |P_{l,i}| \\ P_i^{\min} \leq P_{d,i} \leq P_i^{\max} \quad for \quad i = 1, \ldots, n \end{array} \tag{12}$$

where n is the number of storage units. The optimal solution of this function can be written as in (13) [21].

$$\lambda^* = \frac{\left(\sum\limits_{i=1}^{n} \frac{a_i}{2b_i} - \sum\limits_{i=1}^{n} |P_{l,i}|\right)}{\sum\limits_{i=1}^{n} \frac{1}{2b_i}} \tag{13}$$

where λ^* is the optimal incremental cost for each storage unit.

In this paper, to achieve the noted optimal point, the iterative process in [21] is used to optimize the cost function for storage units, which includes the following distributed updating rules.

$$\lambda_i[k+1] = \sum_{j \in N_i} d_{ij} \cdot \lambda_j[k] + \alpha \cdot P_{v,i}[k] \tag{14}$$

$$|P_{d,i}[k+1]| = \left(\frac{-\lambda_i[k+1] + a_i}{2 \cdot b_i}\right) \tag{15}$$

$$P'_{v,i}[k+1] = P_{v,i}[k] + (|P_{d,i}[k+1]| - |P_{d,i}[k]|) \tag{16}$$

$$P_{v,i}[k+1] = \sum_{j \in N_i} d_{ij} \cdot P'_{v,j}[k] \tag{17}$$

where $P_{v,i}$ is the difference between the current state of battery charge with respect to the value in the last time interval. This is the value shared by the neighbors to contribute, as set in the algorithm.

In matrix form, the noted equations can be shown in the forms given in (18)–(21).

$$\lambda[k+1] = D \cdot \lambda[k] + \alpha \cdot I_n \cdot P_V[k] \tag{18}$$

$$|P_d[k+1]| = B \cdot \lambda[k] + F \tag{19}$$

$$P_v[k+1] - |P_d[k+1]| = P_v[k] - |P_d[k]| \tag{20}$$

$$P_v[k+1] = D{\cdot}B{\cdot}(D - I_n){\cdot}\lambda[k] + (D + \alpha{\cdot}D{\cdot}B){\cdot}P_v[k] \tag{21}$$

where

$$F = \begin{bmatrix} \frac{a_1}{2b_1} & \frac{a_2}{2b_2} & \cdots & \frac{a_n}{2b_n} \end{bmatrix}^T \tag{22}$$

$$B = diag(\begin{bmatrix} \frac{-1}{2b_1} & \frac{-1}{2b_2} & \cdots & \frac{-1}{2b_n} \end{bmatrix}) \tag{23}$$

based on [21], these equations converge to:

$$\lambda[\infty] = [\ \lambda^* \quad \lambda^* \quad \ldots \quad \lambda^*]_n \quad = \lambda^*{\cdot}1_n \tag{24}$$

$$1_n{\cdot}|P_d[\infty]| = 1_n{\cdot}B{\cdot}\lambda[\infty] + 1_n{\cdot}F \tag{25}$$

$$P_v[\infty] = [\ 0 \quad 0 \quad \ldots \quad 0]_n = \quad 0_n \tag{26}$$

$$1_n{\cdot}(P_v[\infty] - |P_d[\infty]|) = 1_n(P_v[0] - |P_d[0]|) \tag{27}$$

by initiating P_v and P_d in (27) through (28):

$$\begin{array}{l} P_{v,i}[0] = -|P_{l,i}| \\ P_{d,i}[0] = 0_n \end{array} \tag{28}$$

We can rewrite (27) using (25), as in (29):

$$1_n{\cdot}|P_d[\infty]| = -1_n(P_v[0]) = \sum_{i=1}^{n} |P_{l,i}[0]| \tag{29}$$

Therefore, (29) can be rewritten as:

$$\sum_{i=1}^{n} |P_{l,i}[0]| = -\sum_{i=1}^{n} \frac{1}{2{\cdot}b_i}{\cdot}\lambda^* + \sum_{i=1}^{n} \frac{a_i}{2{\cdot}b_i} \tag{30}$$

$$\lambda^* = \frac{(\sum\limits_{i=1}^{n} \frac{a_i}{2b_i} - \sum\limits_{i=1}^{n} |P_{l,i}|)}{\sum\limits_{i=1}^{n} \frac{1}{2b_i}} \tag{31}$$

So, the storage units' incremental cost converges to the optimal point. The proposed mixed control approach can provide a robust and optimal over- and under-voltage control in a distribution network. To study the dynamic operation of this technique, the network internal states—such as voltage and current of PVs and storage units—are not considered, as these parameters have faster response times compared with storage unit output power [2]. In other words, these parameters are stabilized faster than output power. Therefore, the proposed control approach determines the dynamic of the network, as given in Figure 5, which illustrates the proposed approach with a flowchart.

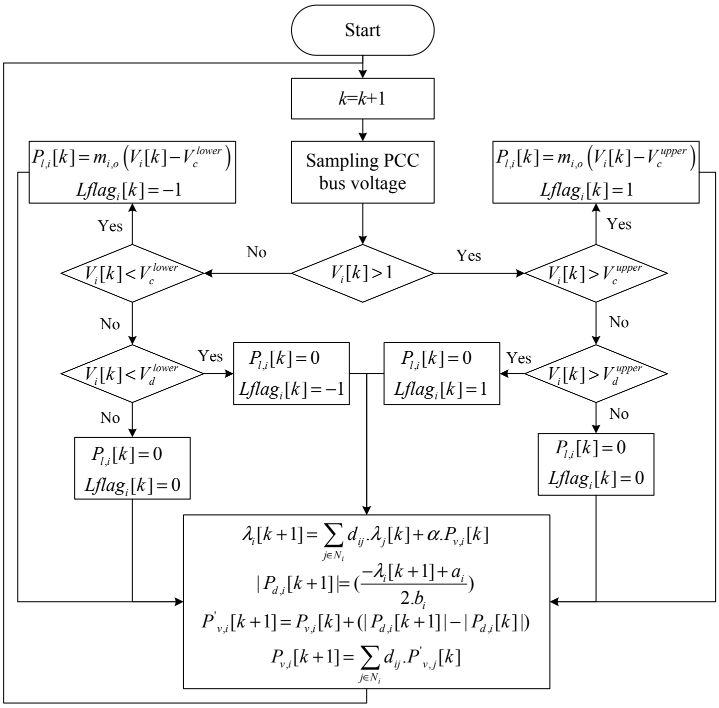


Figure 5. Flowchart of the proposed approach.

3. Case Studies

3.1. Case 1

In the first case, the aim is to compare the performance of the proposed approach with other approaches listed in the literature. Two approaches, including active power curtailment (APC) and storage unit fair sharing for voltage support as listed in [2,7], are considered for the purpose of comparison. A simple and standard radial network with six buses, three PVs and three storage units is simulated with the different voltage support approaches. This test system is shown in Figure 6. The technical data of the network and resources are shown in Tables 1–3. In order to examine the performance of the voltage support approaches considering different network modes, a generation profile given in Figure 7 is used for PVs.

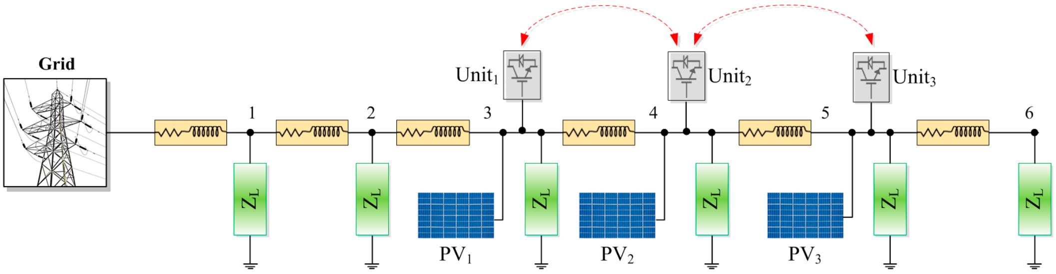


Figure 6. Six-bus test system.

Table 1. Network parameters.

Network voltage level	10 kV
Line impedance between buses	0.3766 + 0.2550i
Load in each bus (kW)	100

Table 2. PVs parameters.

PV	1	2	3
Location (bus)	3	4	5
Rating (kW)	2000	1000	1000

Table 3. Storage units' parameters.

Storage Unit	1	2	3
Location (bus)	3	4	5
Rating (kW)	600	400	550
a_i	0.91	0.91	0.91
b_i	0.04	0.03	0.02

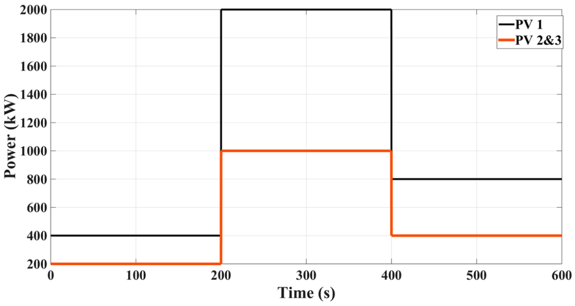


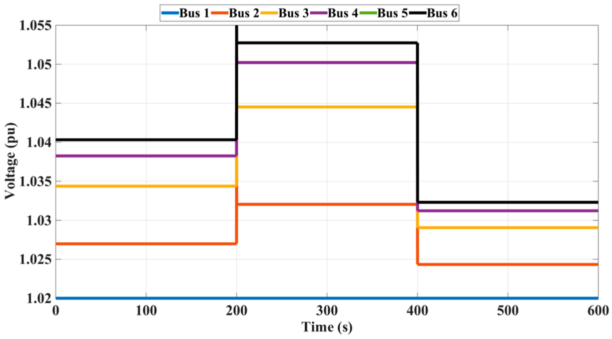
Figure 7. Generation profile of PVs.

In the first scenario, the performance of APC approach [7] is considered for voltage support. The parameters of this control approach for each PV is given in Table 4. Figure 8 shows the bus voltages and PV generation when this control coordination approach is applied to deal with over-voltages.

As it can be seen in this figure, during t = 0–200 s and t = 400–600 s, all voltages are less than the critical limit, therefore, no curtailment is required for the PVs' power. However, during t = 200–400 s, as bus 4 and 5 voltages pass the critical limit, PVs at these buses will have 191.45 kW and 12.65 kW power curtailment, respectively.

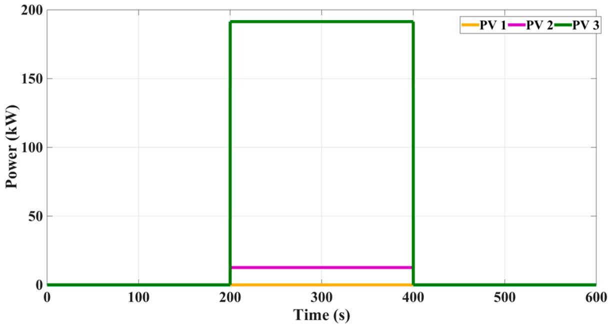
Table 4. Active power curtailment (APC) parameters.

$V_{cri.}$	**1.05 pu**
Droop coefficient of PV 1	20 kW/V
Droop coefficient of PV 2	10 kW/V
Droop coefficient of PV 3	10 kW/V



(**a**)

Figure 8. *Cont.*



(**b**)

Figure 8. Voltage support simulation results based on APC approach, (**a**) bus voltages; (**b**) PVs' power curtailment.

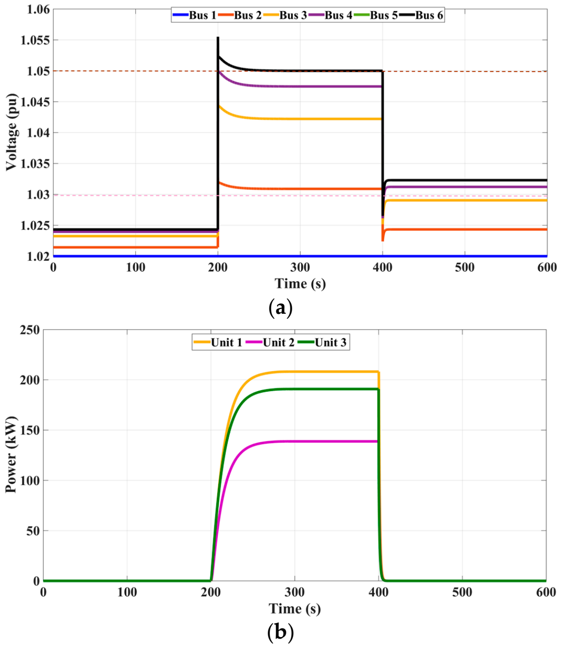
In the second scenario, the performance of distributed fair power sharing [2] is considered for the storage units. In this case, the last node of the network is considered as the critical node with the aim to regulate its voltage to less than 1.05 pu, with equal sharing of storage units. The resulting voltages and power of storage units are shown in Figure 9. The storage units contribute during t = 200–300 s to deal with over-voltage. The sharing of the storage units at the steady-state indicate that the fair share is achieved, as in the following;

$$\frac{P_1}{P_1^{\max}} = \frac{208.19}{600} = 0.347$$

$$\frac{P_2}{P_2^{\max}} = \frac{138.79}{400} = 0.347$$

$$\frac{P_3}{P_3^{\max}} = \frac{190.84}{550} = 0.347$$

Based on the cost function defined for the storage units, the total cost of storage units' utilization in this case is 486.3762 kW.



(**a**)

(**b**)

Figure 9. Voltage support simulation results based on approach in [1], (**a**) bus voltages; (**b**) storage units' charging.

In the third scenario, the performance of the proposed approach in this test system is assessed. The results are provided in Figure 10. It can be seen that during t = 200–400 s all three storage units converge to the optimal incremental cost while the local storage unit contribution converges to zero. The total storage unit utilization is 446.4766 kW, which is less than the case with fair sharing.

In the last scenario, the communication failure is modeled in the system. There is a communication link failure between storage unit 1 and 2 during t = 100–250 s. Figure 11 shows the results; at t = 200 s, while the network goes to over-voltage control mode, only storage units 2 and 3 contribute to voltage support, as storage unit 1 is unaware of the over-voltage situation. However, at t = 250 s, as the communication link becomes available, storage unit 1 starts to contribute and all storage units converge to the value, the same as when there was no communication failure. So, it can be seen that a communication failure may disrupt utilizing all the storage units; however, the optimal utilization of the remaining units is still guaranteed.

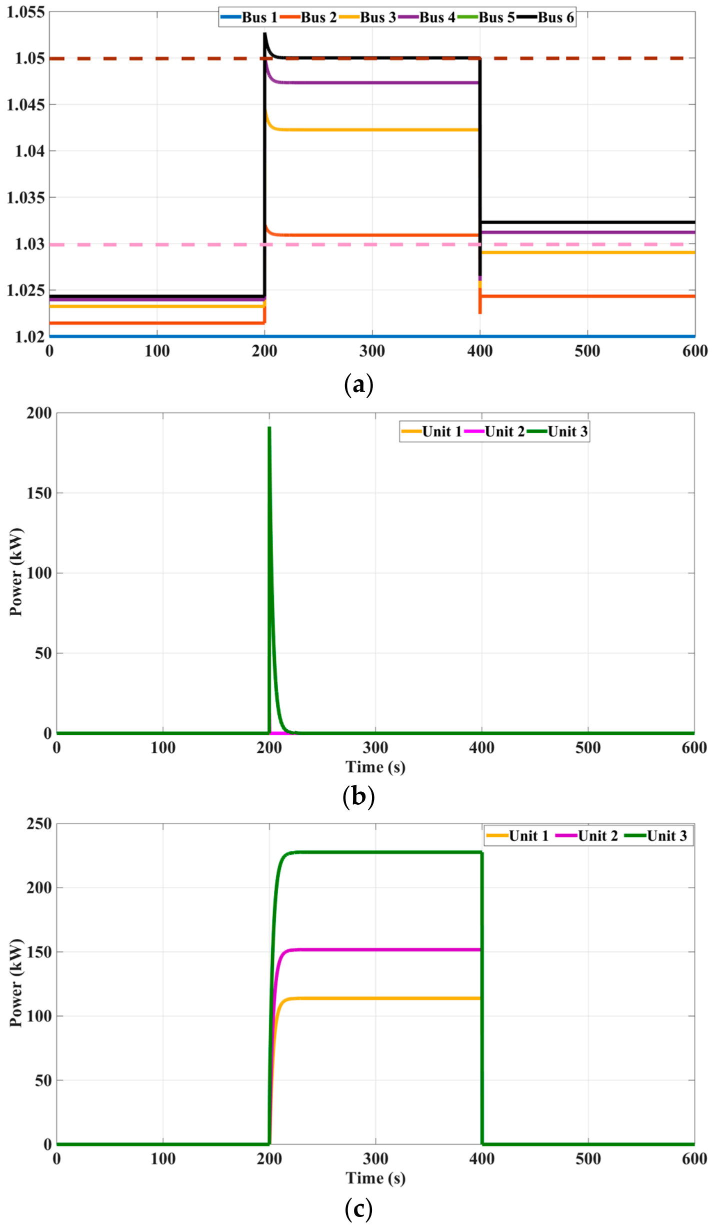
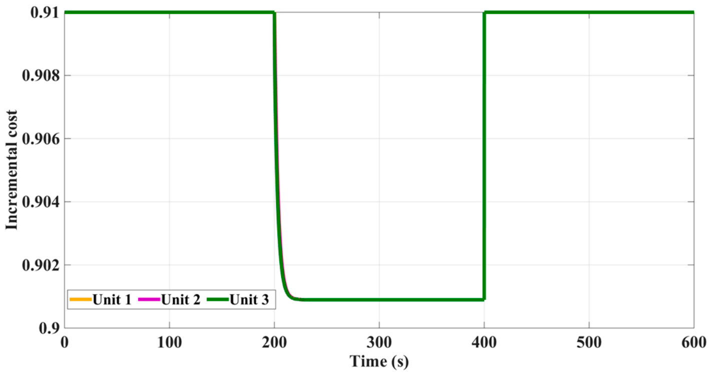
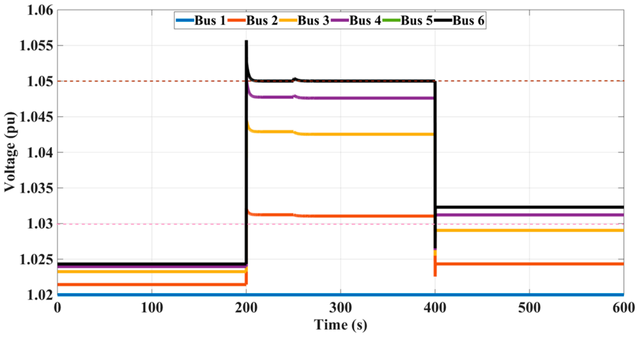


Figure 10. *Cont.*

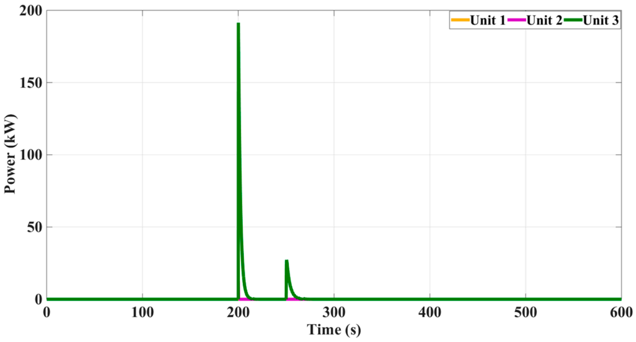


(**d**)

Figure 10. Voltage support simulation results based on proposed control approach, (**a**) bus voltages; (**b**) local contribution of storage units; (**c**) distributed contribution of storage units; (**d**) incremental cost of storage units.



(**a**)



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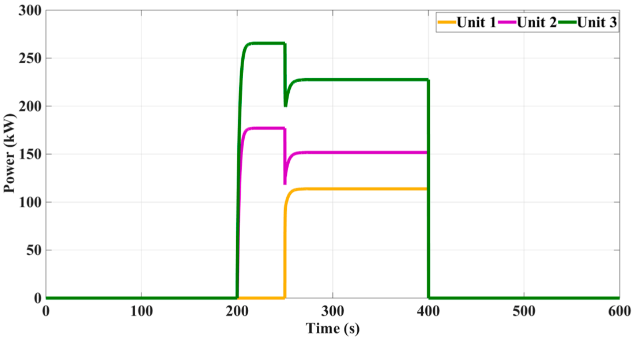
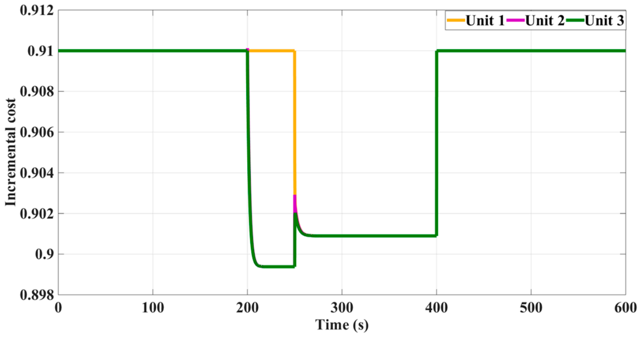


(**c**)

Figure 11. *Cont.*



(**d**)

Figure 11. Impact of communication failure on the proposed control approach, (**a**) bus voltages; (**b**) local contribution of storage units; (**c**) distributed contribution of storage units; (**d**) incremental cost of storage units.

3.2. Case 2

In the second case, the aim is to assess the performance of the proposed approach on a large standard loop system with different network loading modes. IEEE 33 bus system is considered for this purpose, as shown in Figure 12 [22]. A loop configuration of this test system is considered, which includes eight storage units with the technical details listed in Table 5. It is assumed buses have the same peak generation and peak load that are listed in Reference [22]. Therefore, the same load and generation profile shown in Figure 13 is considered for all buses.

To apply the proposed approach on this test system, the voltage limits listed in Table 6 are used.

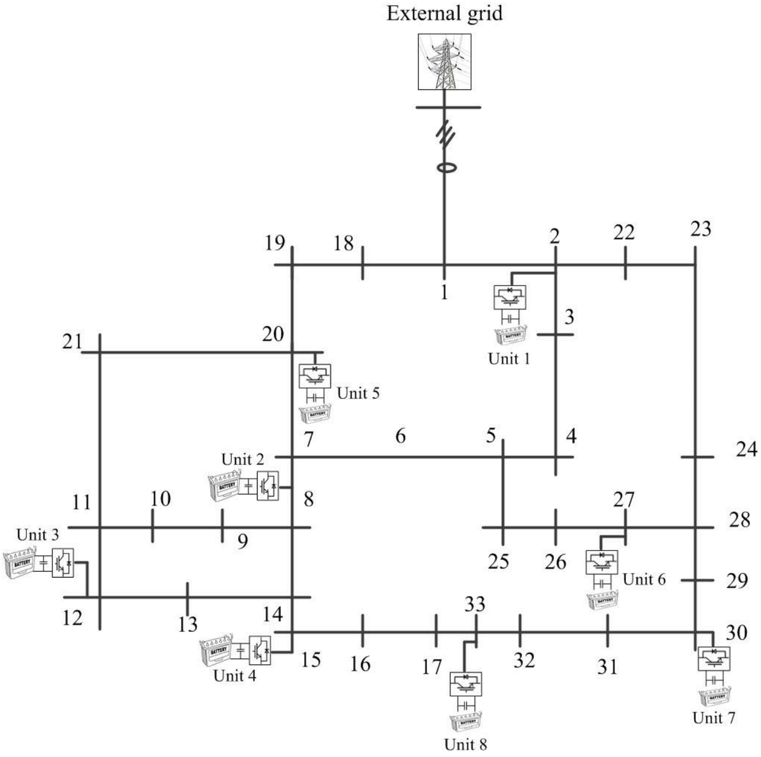


Figure 12. IEEE 33 bus test system.

Table 5. Storage units' parameters.

Storage Unit	**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	0.90	0.91	0.90	0.91	0.90	0.91	0.90	0.91
b_i	0.12	0.11	0.10	0.09	0.12	0.11	0.09	0.08

Table 6. Voltage limits.

Parameter	**Voltage (pu)**
$V_p{}^{upper}$	1.06
$V_c{}^{upper}$	1.05
$V_d{}^{upper}$	1.03
$V_d{}^{lower}$	0.97
$V_c{}^{lower}$	0.95
$V_p{}^{lower}$	0.94

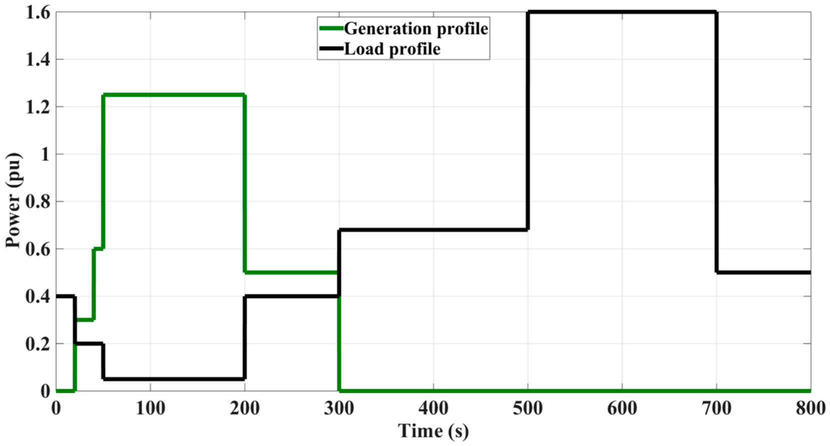


Figure 13. Profile of load and generation at each node.

The proposed approach is applied to this standard test system, and the results are provided in Figure 14. The results in Figure 14 can be described as in the following sequence:

(1) t = 0–50 s: storage units are not required to contribute in voltage support, as the network is in normal mode.

(2) t = 50–200 s: voltage at bus 33 passes the upper critical limit; consequently, network enters the over-voltage control mode and storage units start charging to reduce the network voltages.

(3) t = 200 s: all voltages are in normal mode, therefore no coordination for voltage control is required at this point.

(4) At t = 500–700 s, the network goes to the under-voltage control mode. As a result, storage units start discharging power to increase the bus voltages.

(5) At t = 700 s, the network goes to normal voltage operating mode, therefore, the storages will not need to discharge anymore at this point.

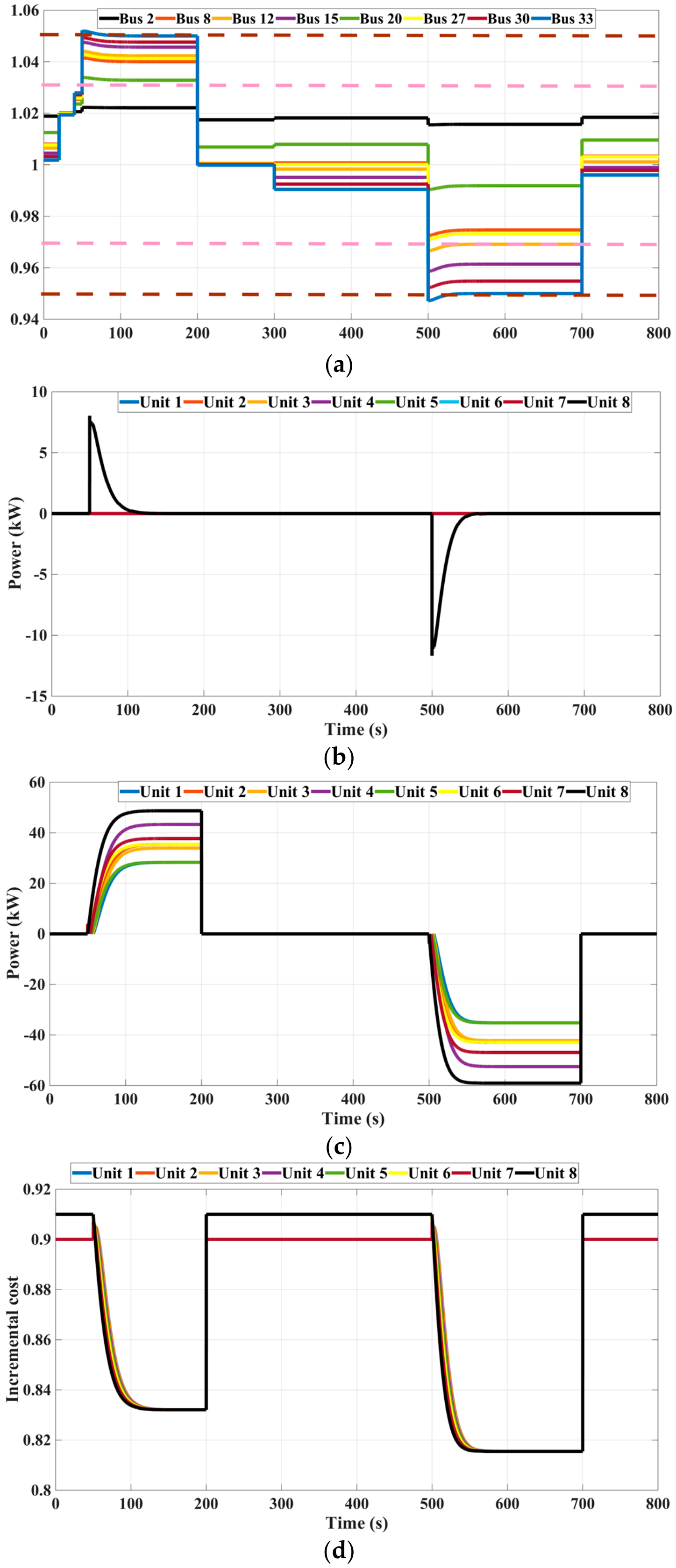


Figure 14. Voltage support simulation results based on the proposed control approach, (**a**) storage unit bus voltage; (**b**) local contribution of storage units; (**c**) distributed contribution of storage units; (**d**) incremental cost of storage units.

4. Discussion

Optimal cooperative management of energy storages in a distribution network is proposed in this paper to deal with voltage violations caused by increased PV penetration and peak load demand. The proposed method was applied to two different networks, radial and loop test systems. In the first case using the radial network, we considered four scenarios associated with an over-voltage issue. In the first two scenarios, existing methods in the literature—namely, APC and storage units fair sharing for voltage support—were applied for comparison purposes. As it can be seen from the results using APC, this method can keep the voltage rise in the allowable range, but at the expense of curtailing PV output. This approach would also not offer a solution for peak load voltage drop. Using the storage units fair sharing method showed significant improvement to avoid energy curtailment in the network. However, this method does not utilize the storages efficiently. In this case, total storage power required to resolve voltage rise was 486.37 kW. However, the proposed method in this paper, which was simulated in the third scenario, showed that only 446.47 kW was required to deal with voltage rise issue in the network. Finally, in the fourth scenario, we also considered communication failure using the proposed method. The results showed that the communication failure has no effect on the voltage control robustness, and still would optimize the storage units with available communication links. It is also worth noting that, in this method, as soon as the communication links are available, the optimization will revert back to the original mode of operation, as if there was not a communication failure.

Further, in case 2 with a larger loop test system, different loading and PV generation modes were introduced to assess the performance of the proposed approach, considering normal and over- and under-voltage operating situations. The results showed the voltage issues were resolved consistently during all the noted modes of operation, with optimal utilization of storage resources.

5. Conclusions

This paper proposed a new optimal cooperative voltage support approach for coordination of storage units in a distribution network. The main objective of the work was defined as improving the voltage profile along a distribution network through both local and distributed control approaches while considering the voltage security constraints. To this end, three network modes (named as over-voltage, normal, and under-voltage control modes) were defined, and a hybrid control approach was applied accordingly to coordinate multiple storage units and to provide robust and efficient voltage support in the distribution network. The performance of the proposed approach was studied on two different test systems under different working scenarios, and the results demonstrated the effectiveness and applicability of this approach compared to conventional methods. Computer simulations also showed that the proposed approach could provide efficient voltage support in different loading modes of the distribution network. Additionally, it was demonstrated that this approach is not sensitive to communication failure, and the optimal utilization of storage units could be guaranteed even in failure modes.

Author Contributions: Ghassem Mokhtari, Ghavameddin Nourbakhsh and Amjad Anvari-Moghadam developed the model. Ghassem Mokhtari and Aminmohammad Saberian simulated the case studies. Ghassem Mokhtari, Ghavameddin Nourbakhsh and Negareh Ghasemi wrote the manuscript. Amjad Anvari-Moghadam and Aminmohammad Saberian provided their comments on the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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