POWER MANAGEMENT IN LOOP DISTRIBUTION NETWORK WITH MULTIPLE ENERGY STORAGE UNITS (ESU)

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***Abstract*—This paper proposes a distributed control approach to coordinate multiple energy storage units (ESUs) to avoid violation of voltage and thermal constraints, which are some of the main power quality challenges for future distribution networks. ESUs usually are connected to a network through voltage source converters.Inthispaper,bothESUconvertersactiveandreactive powerareusedtodealwiththeabovementionedpowerqualityis- sues.ESUs'reactivepowerisproposedtobeusedforvoltagesup- port, while the active power is to be utilized in managing network loading. Two typical distribution networks are used to apply the proposed method, and the simulated results are illustrated in this paper to show the effectiveness of thisapproach.**

***Index Terms*—Consensus algorithm, distributed control, distri- butionnetwork,energystorageunit(ESU),networkloadingman- agement, voltage support.**

I. Introduction

AS asustainablesolutionforfutureenergycrisis,itisan- ticipatedthatfuturedistributionnetworkswillseeawide-spread use of renewable energy sources such as PV,windtur-bine and fuel cell [1]. Distribution networkswithrenewableenergy sources can encounter two main challenges.AtypicalloadcurveforNSWinAustralia[2]showsthatd uringthepeakloadperiod,generationisnormallyloworzero,which maycause voltage drop along the network [3]. On theotherhand,in peak generation period, when generated powerexceedstheload, surplus power is injected to the grid. This willcausere- versepowerandhencemayresultinvoltagerisealongthenet-work [4]–[6]. Additionally, in both peak generationandpeakloadperiods,thermalconstraintsforlineandpo wertransformer can be violated[7].

The strategies suggested by researchers to avoid these issues can be divided in the followingcategories:

1) Network upgrading. References [8]–[10] propose the in- crease of conductor cross section to deal with voltage rise. This approach requires high investment cost which is not attractive forutilities.

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Changing network static set points such as transformer tap changers [9], [11]. This approach is not practical due to randomness of load and generation which needs frequent changes of setpoints.

2) Active power curtailment [12], which reduces the energy efficiency.

3)

The unbalance between the generated power and load, during boththehighloadandhighgenerationperiods,causesthenoted issues [13]. As a result, the introduction of energy storage unit (ESU) as a buffer can be a promising solution which can store surplus power during the peak generation periods and use it in peak load periods[14]–[16].

The main challenge in the utilization of multiple ESUs is the coordination control strategy [17]. There are three types of co- ordinationstrategiesthatcanbetaken.Thefirststrategycanbe provided through centralized manner in which a central con- troller coordinates ESUs [18], [19]. The drawback of this ap- proach is that it would require extensive data base with high speedandfastcalculatingcomputers,alongwithbroadbandnet- works. This can be too expensive for the current state of art. This can also be less reliable due to communication failure and computer freezing [20]. The second approach is the localized controlstrategy,basedonlocalmeasurementsonly,suchasthe ones proposed in [12] and [21]. This control strategy is robust in the sense that only local measurements are utilized. How- ever, it cannot effectively utilize all available resources in the network due to the lack of broader information. A distributed controlstrategy,thethirdapproach,canbeasefficientasacen- tralized approach while avoiding its drawbacks [22]. However, the robustness of this approach still depends on the communi- cationlinks.

This paper proposes an effective and robust approach which can coordinate multiple ESUs to manage and control voltage and loading in distribution networks. As voltage needs fast and robust control, a combined localized and distributed control approach is proposed to regulate the ESUs reactive power to deal with voltage issues. In addition, a distributed control strategy based on consensus algorithm is proposed to manage network loading,whichdividestherequiredactivepowerequallyamong ESUswithrespecttotheirmaximumavailableactivepower.

II. ProposedApproach

National standards usually allow a maximum of 6% voltage variation in distribution network [12]. Considerthe $S^{min\_desirable}$ $S^{min\_critical}$ $S^{max\_desirable}$ $S^{max\_critical}$

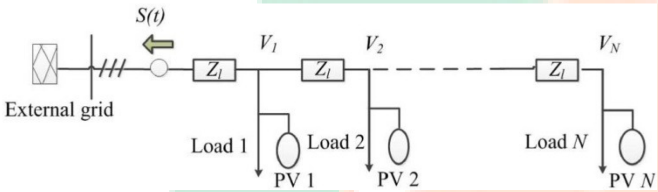

Fig. 1. Radial distribution network with multiplePVs.

distribution network with PV as the renewable energy sources, as shown in Fig. 1. Distribution network is designed in such a way that the voltage level of different nodes is within the standard limits, in normal operating condition. However, practical measurements show that the permissible lower voltage limit ($V^{min\_permissible}$)in critical buses is usually violated in peak load periods, which usually occur in the evenings when PVsdo not generate any active power. In addition, the permissible lower limit for network loading ($S^{min\_permissible}$)may also be violated during this period, which is notacceptable.

Similarly, the violations can occur during the midday when network is in its low load period, while the PVs are in their maximumgenerationmode.Duringthisperiod,thepermissible upper voltage limit ($V^{max\_permissible}$) and permissibleupper network loading limit ($S^{max\_permissible}$) can bereached.TheapproachofthispaperistocoordinateESUs'activeandreactive power to avoid theseproblems.

ESUsareaddedtothenetworkofFig.1tocopewiththeproblems. The proposed distributed control structure for coordinationofESUisshowninFig.2.ThedashedarrowsinFig.2(a) show the information flow, where the neighboring ESUs are communicated to coordinate their operation. The proposed internalcontrolstructureforeachESUisshowninFig.2(b).The referencevalueforESU'sactiveandreactivepower($P^*_{ESUi}(t)$ and $Q^*_{ESUi}(t)$) depend on information state of each ESUandits neighbors. As noted before, the proposed control structure includes voltage and network loading management. Details of the proposed approach are presented below.

A. Network Loading Management

In this paper, a consensus algorithm is proposed to be used to share the required active power with the same ratio among ESUs, for network loading management. In this algorithm, consensus is achieved by sharing variable of interest, called the information state. Consensus algorithm has been used in different applications of distributed control. In [23] and [24], it is used to align multiple wheeled mobile robots. Reference [25] applied this algorithm to coordinate unmanned air vehicles for fire monitoring.

In this application, a higher control level named the leader is defined to initiate the ESUs coordination. The internal control structureofleaderisshowninFig.3.TheleadermonitorsS(t), the drawn power from $(-)$or injected to $(+)$the external grid (higher voltage level network), and use this as the controllable variableforthenetworkloadingmanagement.Fourthreshold limits; and withnegativevaluesand and with positive valuesare

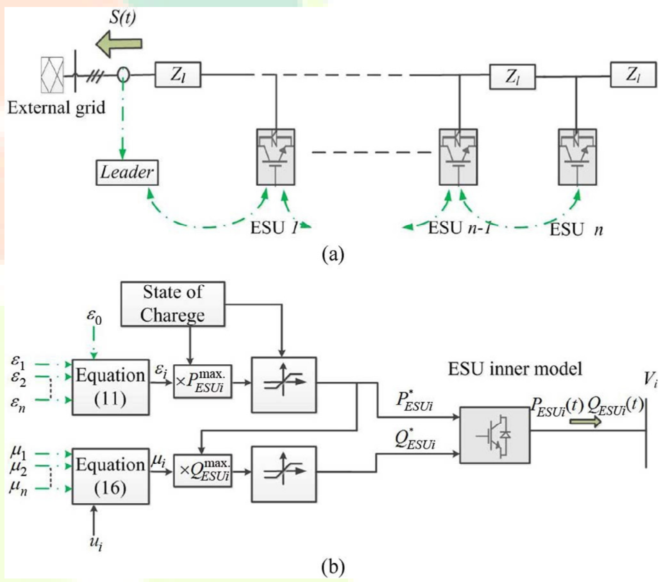

Fig. 2. Proposed approach. (a) Distributed control structure. (b) Internal control structure for eachESU.

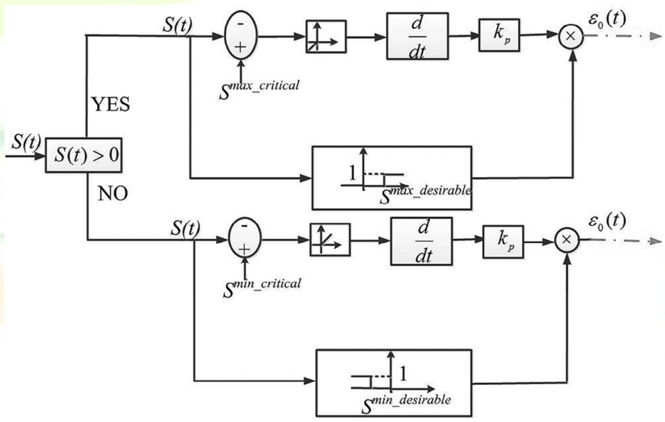

Fig. 3. Proposed control structure forleader.

considered to determine the network operation mode. In peak load period, if $S(t)$ is more than $S^{min\_desirable}$, the network is in its normal operation mode and ESUs coordination is not needed. However, if $S(t)$ violates $S^{min\_critical}$, ESUs coordinationisinitiatedbyleaderanditiscontinueduntilthevalueof $S(t)$ becomes more than $S^{min\_desirable}$. The same procedure is applied for high generationperiod.

The proposed distributed control strategy for ESUs active power can be written in a general formas

$$\varepsilon_i(t) = f_i\left(c_{i0}(t).\varepsilon_0(t), c_{i1}(t).\varepsilon_1(t), \ldots, c_{in}(t).\varepsilon_n(t)\right) \quad (1)$$

whereis ε_0 the information state of leader, ε_i is the information stateofthe i thESUactivepowerwhichiscommunicatedamong neighboring ESUs, c_{ij} denotes the communication link between the i th and j thESUs, $c_{ij}=1$; if the j th ESUsendsinformationto the i th,otherwise $c_{ij}=0$. Inaddition, $c_{i0}=1$; ifthe i thESU can get information from the leader,othe $c_{i0}=0$ me-varyingcoefficientscanbeorganizedinamatrixof the complete communication topologyas $c_{ii}=1$

$$C(t) = \begin{bmatrix} c_{10}(t) & c_{11}(t) & \ldots & c_{1n}(t) \\ \vdots & \vdots & \ddots & \vdots \\ c_{n0}(t) & c_{n1}(t) & \ldots & c_{nn}(t) \end{bmatrix} \quad (2)$$

Two general objectives need to be achieved to coordinate ESUs for network loading management. The first objective is todesignacontrolforeachESUtoreducethenetworkloading less than the critical limits. In other words, in peak generation period (3) and in peak load period (4) need to be met at equilibrium point of ESUs coordination:

$$S(t) < S^{\max\_critical} \quad (3)$$

$$S(t) > S^{\min\_critical} \quad (4)$$

The second objective is to design a control for each ESU in suchawaythattherelationshipin(5)ismetatequilibriumpoint ofESUscoordination.Inotherwords,therequiredactivepower istobesharedatthesameratioasitsmaximumavailableactive power for each ESU ($P^{\max}_{ESU\,i}$). As shown in Fig. 2(b), the value of $P^{\max}_{ESU\,i}$ depends on ESU state of charge and can be considered for a specified period of time (for example, 1 hour). In other words, for 1 hour, the value of $P^{\max}_{ESU\,i}$ is the maximum active power which the ith ESU can continuously support. In this way, it can be said that the required active power will be shared with respect to ESU state of charge which is an important parameter for theESU:

$$\frac{P_{ESU1}}{P^{\max}_{ESU1}} = \frac{P_{ESU2}}{P^{\max}_{ESU2}} = \ldots = \frac{P_{ESU\,n}}{P^{\max}_{ESU\,n}}. \quad (5)$$

Thefollowingproceduresneedtobefollowedtoachievethe noted control objectives.

If $S(t)$ passes $S^{max\_critical}$ limit, the leader should initiate the consensus algorithmby

$$\dot{\varepsilon}_0(t) = k_p.\left(S^{\max\_critical} - S(t)\right) \quad (6)$$

Similarly, if $S(t)$ violates $S^{min\_critical}$ limit, the leader should alsoinitiate

$$\dot{\varepsilon}_0(t) = k_p.\left(S^{\min\_critical} - S(t)\right) \quad (7)$$

Based on consensus algorithm, the information state of each ESU can be determinedas

$$\dot{\varepsilon}_i(t) = -\sum_{j=0}^{n} a_{ij}(t).(\varepsilon_i(t) - \varepsilon_j(t)) \quad (8)$$

where $a_{ij}(t)$ is the (i,j) entry of adjacencymatrix; $a_{ij}(t) > 0$ if and $c_{ij}(t)=1$ $a_{ij}(t)=0$ otherwise.

In real case, the interaction among ESUs and leader occurs at discrete time steps. So, (6), (7) and (8) are replaced with(9), (10) and (11),respectively:

$$\varepsilon_0[t] = \varepsilon_0[t - t_d] + k_p.\left(S^{\max\_critical} - S[t]\right) \quad (9)$$

$$\varepsilon_0[t] = \varepsilon_0[t - t_d] + k_p.\left(S^{\min\_critical} - S[t]\right) \quad (10)$$

$$\varepsilon_i[t] = \sum_{j=0}^{n} d_{ij}[t].\varepsilon_j[t - t_d] \quad (11)$$

where $d_{ij}[t]$ can be found in each discrete time dataexchangeby

$$d_{ij}(t) = \frac{c_{ji}[t - t_d]}{\sum_{j=0}^{n} c_{ji}[t - t_d]}. \quad (12)$$

For the entire network, $d_{ij}[t]$ can be considered as the (i,j) entry of a row stochastic matrix in which the sum of each row is equal to1.

Finally, the required contribution of each ESU at each time step is updatedby

$$P^{*}_{ESU\,i}[t] = \varepsilon_i[t] \times P^{\max}_{ESU\,i}. \quad (13)$$

B. Voltage ConstraintsManagement

Similar to network loading control, four limits areconsid- ered for voltage control. Toavoidovervoltage, $V^{max_desirable}$and $V^{max_critical}$determine the network operation mode. If all ESU bus voltages are less than $V^{max\_critical}$, the network isin normal operation mode and ESUs reactive power coordina- tion is not needed. However, if the bus voltage of any ESU vi- olates the limit, it initiates the distributed algorithm to support thevoltage.Thecoordinationwillcontinueuntilallvoltagesare reduced to less than $V^{max\_desirable}$. In this situation, all ESUs decrease their reactive power step by step. The same procedure is applied to avoid under-voltage, inwhichcase $V^{min_desirable}$and $V^{min_critical}$determine the networkoperation.

Two objectives need to be achieved to coordinate ESUs' re- active power when required. The first is to design a control for each ESU to keep the voltage within criticallimits(between$V^{max_critical}$and $V^{min\_critical}$). The ESU control as givenin (14) and(15):

$$V_i(t) < V^{\max\_critical} \quad i = 1, \ldots, n \quad (14)$$
$$V_i(t) > V^{\min\_critical} \quad i = 1, \ldots, n. \quad (15)$$

The voltage limit violation is a local problem, not a net- work wide problem. Therefore, it is well suited to design a distributed control such that the most effective ESUs on the vi- olated voltage(s), should contribute more in the reactive power sharing. This strategy is expected to provide the optimum voltage supportmechanism.

AsshowninFig.2(b),thereferencevalueforreactivepower ofeachESUisafunctionofitsbusvoltageandtheinformation state of its neighboring ESUs. Based on this internal control structure, it is proposed that the information state of each ESU reactive power is updated in discrete time interval $t_d$as given by

$$\mu_i[t] = s_{ii}[t].u_i[t] + \sum_{j \in N_i} s_{ij}[t].\mu_j[t - t_d] \quad (16)$$

where μ_i is the information state for the ith ESU's reactive power which is communicated to its neighboring ESUs, u_i is a localized control term to assure a robust control of ESU bus

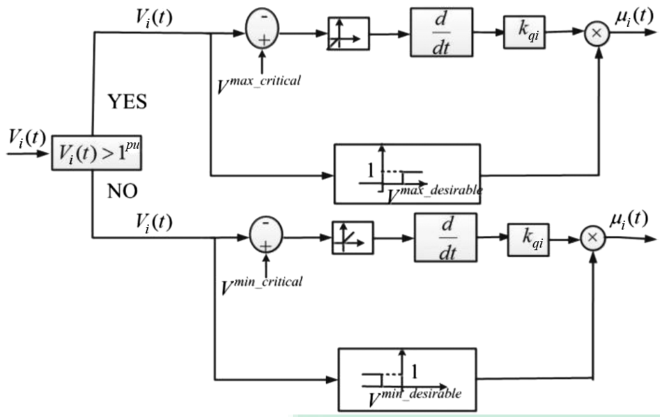

Fig. 4. Proposed localized voltage control for eachESU.

voltage. This value is determined based on a control structure shown in Fig. 4. In addition, a_{ij} represents transition weights which are potentially time-varying and dependent on communication structure. The weights, determined based on the bus voltage sensitivity to the reactive power, share the required reactive power in efficient way among ESUs (objective 2). This is discussedbelow.

The relationship between changes in power (active andreactive)withchangesinbusvoltagecanbedeterminedbyJacobianmatrixas

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \cdot \begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} \tag{17}$$

where

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix}^{-1} \cdot \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}. \tag{18}$$

TheapproximatesensitivityoftheESUbusvoltagetothereac- tive power can be givenby

$$\frac{\partial V}{\partial Q} = D. \tag{19}$$

Withtheproposedcommunicationstructure,theESUsareonly aware of the value of D_{ji} corresponding to their neighbors. Therefore, the sensitivity matrix is modifiedas

TABLE I
PVsRating

PV	PV1	PV2	PV3	PV4	PV5
Active power (kW)	550	600	500	450	650

If either of the critical voltage limits is violated for anyESU, its localized control term initiates the distributed control strategy basedon

$$u_i(t) = k_{qi}.\left(V^{\max\_critical} - V_i(t)\right) \tag{22}$$

$$u_i(t) = k_{qi}.\left(V^{\min\_critical} - V_i(t)\right). \tag{23}$$

Followingthecontrolinitiation,theinformationstatesofESUs areupdatedineachdiscretetimeintervalbasedon(16).Finally, the required reactive power contribution of each ESU at each time interval is updatedby

$$Q^*_{ESUi}[t] = \mu_i[t] \times Q^{\max}_{ESUi}. \tag{24}$$

By applying this control structure, both objectivesforvoltagesupportcanbeachievedandESUinverterswil lcontributewiththeir reactive power. The complete set of system(25)–(33)forthiscoordinationstrategyisgivenatthebottomofthenextpage,where(25)–(28)modeltheproposeddistributedcontrolstrategyforESUs,(29)and(30)modeltheESUsinternalcontrol.Equa-tion (33) gives the load flow equationswhere $\mathcal{X}$ denotesthein- ternaldynamicsofnetworksuchasstatevariableofESUs,etc.,and $\mathcal{Y}$ isthealgebraicvariablesofnetworksuchasbusvoltages.It is worth noting that the internal dynamicsof network($\mathcal{X}$) arenotconsideredhere.Thisisbecause,thedynamicofinternalvariables are much faster compared with output power.So,itcanbesaidthatthevalueofthesevariablesdiminishmuchfasterthan the output power. As a result, the dynamic ofESUoutputpower is determined by the controller designed inthis paperwhile the inner dynamic of ESUs is ignored.Consequently,theESUs reactive and active power are modeled as in (31) and (32).

III. CaseStudies

$$\overline{D_{ji}} = \begin{cases} D_{ji} & i \in \{N_j \cup j\} \\ 0 & i \notin \{N_j \cup j\}. \end{cases} \qquad (20)$$

Finally, the transition weights are calculated by the following equation:

$$s_{ij}[t] = \frac{\overline{D_{ji}}.c_{ij}[t]}{\sum_{k=1}^{n} \overline{D_{ki}}.c_{ki}[t]}. \qquad (21)$$

It is worth noting that the voltage sensitivities do not change much with respect to the changes in the operating point [26]. Therefore their nominal values are used in this paper to design the transition weights. As a result, the weights are predetermined for each ESU and itsneighbors.

A. Case1

A typical radial distribution network is selected, as the first case, to show the effectiveness of the proposed approach. The networkparametersandloaddetailscanbefoundin[20].There are5PVsconnectedinthisnetworkwithratinglistedinTableI. The network structure with three ESUs and its communication topologyisshowninFig.5.Itisassumedfortheperiodofstudy, allESUscancontinuouslysupportthepowershowninTableII. ItisassumedthatESUinverterratingisincreasedbyjust11.8% to have the ability to supply nearly 50% reactive power while supplying full rated active power. The limits for voltage and network loading are listed in Tables III andIV.

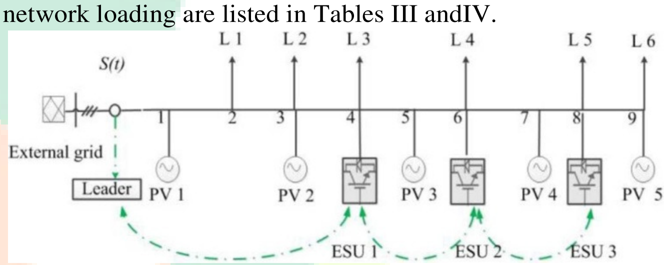

Fig. 5. Radial distribution network with multipleESUs.

TABLEII
AVAILABLE ACTIVE POWER FORESUS

ESU	ESU1	ESU2	ESU3
Active power (kW)	150	200	250

In addition, it is stipulated that the power factor of ESUs shouldbemorethan0.9andtheupperlimitofthereactivepower output is dependent of the active power outputas

$$Q^{\max}_{ESUi} = P_{ESUi} \qquad (34)$$

$0.4843 \times$ $i = 1, 2, 3.$

It is assumed that all loads are in 15% of their maximum. In addition, the PVs generation change from 75% to 95% at $t =$ 100 s . the result for this case is shown in Fig.6.

TABLEIII
VOLTAGE LIMITS IN THE PROPOSED APPROACH

Parameter	Voltage (pu)
$V^{max\_permissible}$	1.06
$V^{max\_critical}$	1.03

TABLEIV
NETWORK LOADING LIMITS IN THE PROPOSED APPROACH

Parameter	Power (kVA)
$S^{max\_permissible}$	2200
$S^{max\_critical}$	1800
$S^{max\_desirable}$	1500

It can beseenbetween and , allvoltagesandnetworkloadingareinthedesirablerange.Therefore,noESUs coordination is needed.However,at, as thePVgeneration increases, the critical upper limit for voltage of ESUs 2 and 3 and network loading is violated. Therefore, the proposed control approach for both voltage and thermal constraints man- agement is initiated. For network loading management, it can be seen that, at the equilibrium point, its value is less than upper

$$u_i[t] = \begin{cases} u_i[t-t_d] + k_{qi}.\left(V^{\max\_critical} - V_i[t]\right) & V_i[t] > V^{\max\_critical} \\ u_i[t-t_d] & V^{\max\_desirable} < V_i[t] < V^{\max\_critical} \\ 0 & V^{\min\_desirable} < V_i[t] < V^{\max\_desirable} \\ u_i[t-t_d] & V^{\min\_critical} < V_i[t] < V^{\min\_desirable} \\ u_i[t-t_d] + k_{qi}.\left(V^{\min\_critical} - V_i[t]\right) & V_i[t] < V^{\min\_critical} \end{cases} \quad i = 1, 2, \dots, n \tag{25}$$

$$\varepsilon_0[t] = \begin{cases} \varepsilon_0[t-t_d] + k_p.\left(S^{\max\_critical} - S[t]\right) & S[t] > S^{\max\_critical} \\ \varepsilon_0[t-t_d] & S^{\max\_desirable} < S[t] < S^{\max\_critical} \\ 0 & S^{\min\_desirable} < S[t] < S^{\max\_desirable} \\ \varepsilon_0[t-t_d] & S^{\min\_critical} < S[t] < S^{\min\_desirable} \\ \varepsilon_0[t-t_d] + k_p.\left(S^{\min\_critical} - S[t]\right) & S[t] < S^{\min\_critical} \end{cases} \quad i = 1, 2, \dots, n \tag{26}$$

$$\mu_i[t] = s_{jj}[t].u_i[t] + \sum_{j \in N_i} s_{ij}[t].\mu_j[t-t_d] \tag{27}$$

$$\varepsilon_i(t) = \sum_{j=0}^{n} d_{ij}(t-t_d).\varepsilon_j(t-t_d) \tag{28}$$

$$Q^*_{ESUi}[t] = \mu_i[t] \quad i = 1, 2, \dots, n \quad \times Q^{\max}_{ESUi} \tag{29}$$

$$P^*_{ESUi}[t] = \varepsilon_i[t] \quad i = 1, 2, \dots, n \quad \times P^{\max}_{ESUi} \tag{30}$$

$$Q_{ESUi}[t] = Q^*_{ESUi}[t] \quad i = 1, 2, \dots, n \tag{31}$$

$$P_{ESUi}[t] = P^*_{ESUi}[t] \quad i = 1, 2, \dots, n \tag{32}$$

$$g(P_{ESU1}, P_{ESU2}, \dots, P_{ESUn}, Q_{ESU1}, Q_{ESU2}, \dots, Q_{ESUn}, \chi, X) = 0 \tag{33}$$

TABLE V
ESUs RATING

ESU	1	2	3	4	5	6	7	8
Active power (kW)	150	60	120	80	100	140	50	40

critical limit (the first aim is achieved). In addition, the ESU contribution is as follows based on the secondobjective:

$$\frac{P_{ESU1}}{P^{\max.}_{ESU1}} = \frac{-74.75}{150} = -0.49$$
$$\frac{P_{ESU1}}{P^{\max.}_{ESU1}} = \frac{-99.67}{200} = -0.49$$
$$\frac{P_{ESU1}}{P^{\max.}_{ESU1}} = \frac{-124.59}{250} = -0.49.$$

In addition, after the generation step change, the ESU voltages follow the pattern based on (35). Accordingly, reactive power sharing among ESUs needs to follow as in (36) to have effective voltage support:

$$V_3 > V_2 > V_1 \quad (35)$$
$$\left|\frac{Q_{ESU3}}{Q^{\max.}_{ESU3}}\right| > \left|\frac{Q_{ESU2}}{Q^{\max.}_{ESU2}}\right| > \left|\frac{Q_{ESU1}}{Q^{\max.}_{ESU1}}\right| \quad (36)$$

The reactive power sharing at the equilibrium point of coordinationisasfollows.Itcanbeseenthattheproposedapproach follows the second objective aimed in thispaper:

$$\left|\frac{Q_{ESU1}}{Q^{\max.}_{ESU1}}\right| = \left|\frac{Q_{ESU1}}{0.4843 \times P_{ESU1}}\right| = \left|\frac{-2.016}{0.4843*124.59}\right| = 0.033$$
$$\left|\frac{Q_{ESU2}}{Q^{\max.}_{ESU2}}\right| = \left|\frac{Q_{ESU2}}{0.4843 \times P_{ESU2}}\right| = \left|\frac{-5.28}{0.4843*124.59}\right| = 0.087$$
$$\left|\frac{Q_{ESU3}}{Q^{\max.}_{ESU3}}\right| = \left|\frac{Q_{ESU3}}{0.4843 \times P_{ESU3}}\right| = \left|\frac{-14.05}{0.4843*124.59}\right| = 0.232.$$

B. Case2

The IEEE 33 bus is used as the second case study to show the effectiveness of the proposed approach in different operation modes. In addition, the effect of communication drop on the proposed approach is studied as well. This is a 12.66-kV loop system with parameters listed in [27]. The network structure and the multiple ESUs are shown in Fig. 7. For the studied period of time, it is assumed that the ESUs can support the active power listed in Table V continuously. In addition, the apparent power than can be supplied by the ESU inverter is assumed to be the same as the ESU rating, i.e., no over-rated inverter is necessary. Therefore, the upper limit of the reactive power output is dependent of the active power outputas

$$\sqrt{S^2_{ESUi} - P^2_{ESUi}} \qquad i = 1, 2, ..Q^{\max.}_{ESUi} = \quad (37)$$

where S_{ESUi} is the rating of the th i ESU inverter. In this case, thepowerfactorcanvarydependingontheESUactivepower.

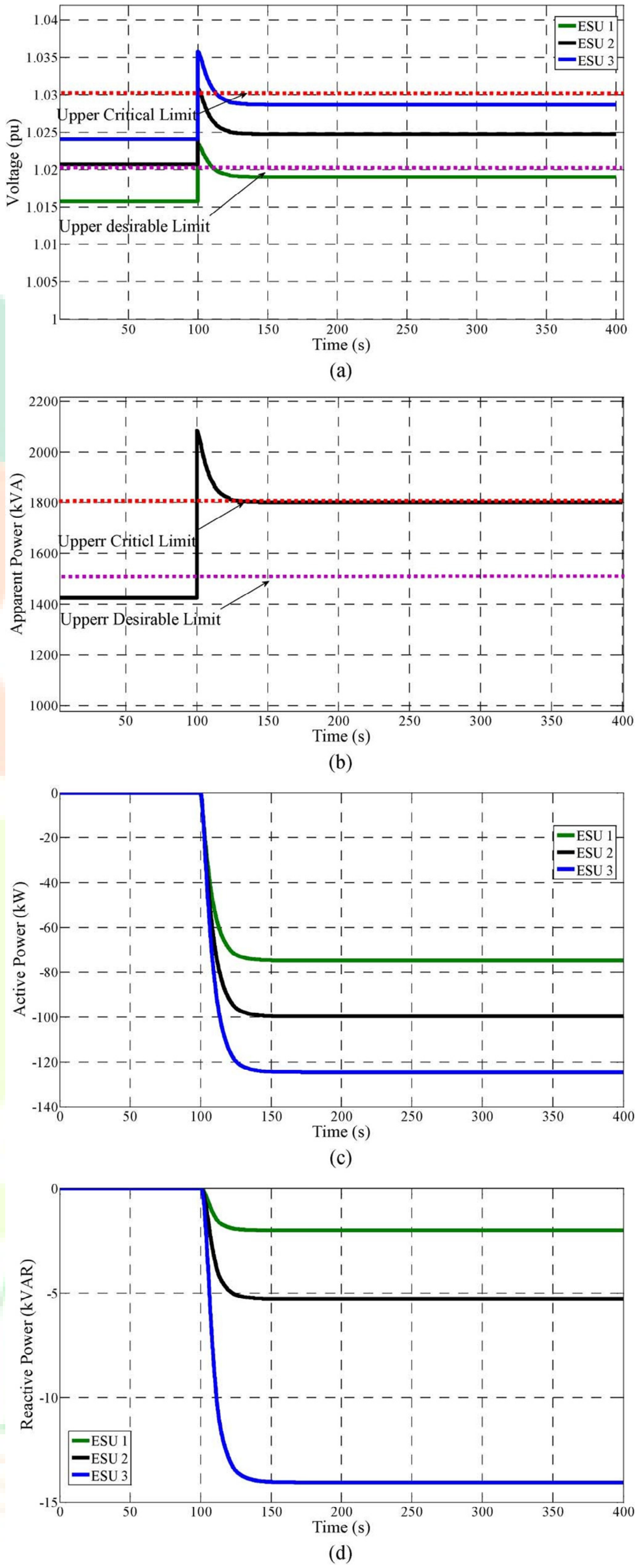

Fig.6. Proposedcontrolapproach.(a)ESUsbusvoltage.(b)Networkloading. (c) ESUs active power. (d) ESUs reactivepower.

Moreover, For the sake of simplicity, it is assumed that the maximum generation power in each bus is equal to maximum load active power in that bus. With respect to these values, it

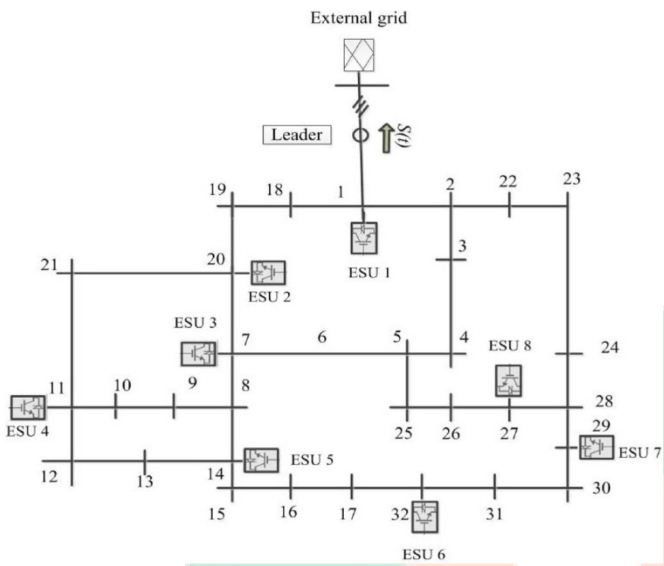

Fig. 7. Loop distribution network with multiple ESUs.

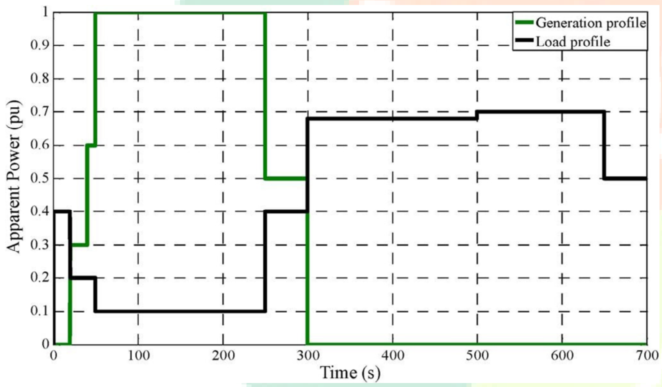

Fig. 8. Load and generation profiles at eachnode.

TABLEVI
VOLTAGE LIMITS IN THE PROPOSED APPROACH

Parameter	Voltage (kV)	Voltage (pu)
$V^{max\_permissible}$	13.41	1.06
$V^{max\_critical}$	13.03	1.03
$V^{max\_desirable}$	12.91	1.02
$V^{min\_desirable}$	12.40	0.98
$V^{min\_critical}$	12.28	0.97
$V^{min\_permissible}$	11.90	0.94

is assumed that all buses have the same generation and load profiles, as shown in Fig. 8. The limits for voltage andnetwork loadingarelistedinTablesVIandVII.

For the system of Fig. 7, it is assumed that ESU information states are updated at each $t_{\overline{n}}$. Moreover, it is assumed that the communication link between ESU 4 and 5 is not availableduring $t = 300$–400 s. Usingtheproposedcontrol approach, Fig. 9 shows the bus voltages, network loading,ESUs

TABLEVII
NETWORK LOADING LIMITS IN THE PROPOSED APPROACH

Parameter	Power (kVA)	Power (pu)
$S^{max\_permissible}$	3000	30
$S^{max\_critical}$	2700	27
$S^{max\_desirable}$	2000	20
$S^{min\_desirable}$	-2000	-20
$S^{min\_critical}$	-2700	-27
$S^{min\_permissible}$	-3000	-30

active power, ESUs reactive power in different time steps. The time sequences of the operation are detailed asfollows:

1) Between 0 s and 50 s, the network loading and all ESUs voltages are in desirable range and no ESUs coordination is needed.
2) At 50 s, injection increases while the network loading passes $S^{max\_critical}$. As a result, the leader initiates the coordination of ESUs active power to reduce the network loading. At $t = 68$ s, the network loading becomelessthan $S^{max\_critical}$ (the first objective is achieved).Itcanbe seen that, at the equilibrium point, the ESUs contribute at the same ratio as their available power (the second objective isachieved).
3) At 250 s, network loading goes to the desirable range. As a result, ESUs reduce their active power contribution step by step, until they stopoperating.
4) At 300 s, critical limits for network loading and the voltage atbus32areviolated.Consequently,ESUsstarttocoordi- nate their active and reactive power. However, due to the communicationlinksdropbetweenESUs4and5,voltage support can only be coordinated for ESUs 5, 6, 7 and 8. Using their localized control term, they can keep the vio- latedbusvoltage(ESU6bus)intherange.Moreover,only ESUs 1, 2, 3 and 4 are coordinated for loading reduction. At $t = 400$ s, communication links becomeavailablebe- tween ESUs 4 and 5. Consequently, the ESU information states for active and reactive power are updated again. At this stage, the information states of ESUs active power are asfollows:

$$\varepsilon_0 = \varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = 0.51 \quad \varepsilon_5 = \varepsilon_6 = \varepsilon_7 = \varepsilon_8 = 0.$$

As can be seen, at the equilibrium point of this coordina- tion, information states of all ESUs active power converge to the value of 0.51. The total required active power there- foreis379.21kW.Thisvalueismorethanthecasewithno communication drop (the result is not shown due to space limitation) which is 291.41kW.

These results show that the communication malfunction does not affect the robustness of the proposed approach, even though it limits the available resources for coor- dination and may somewhat reduce the efficiency of management.

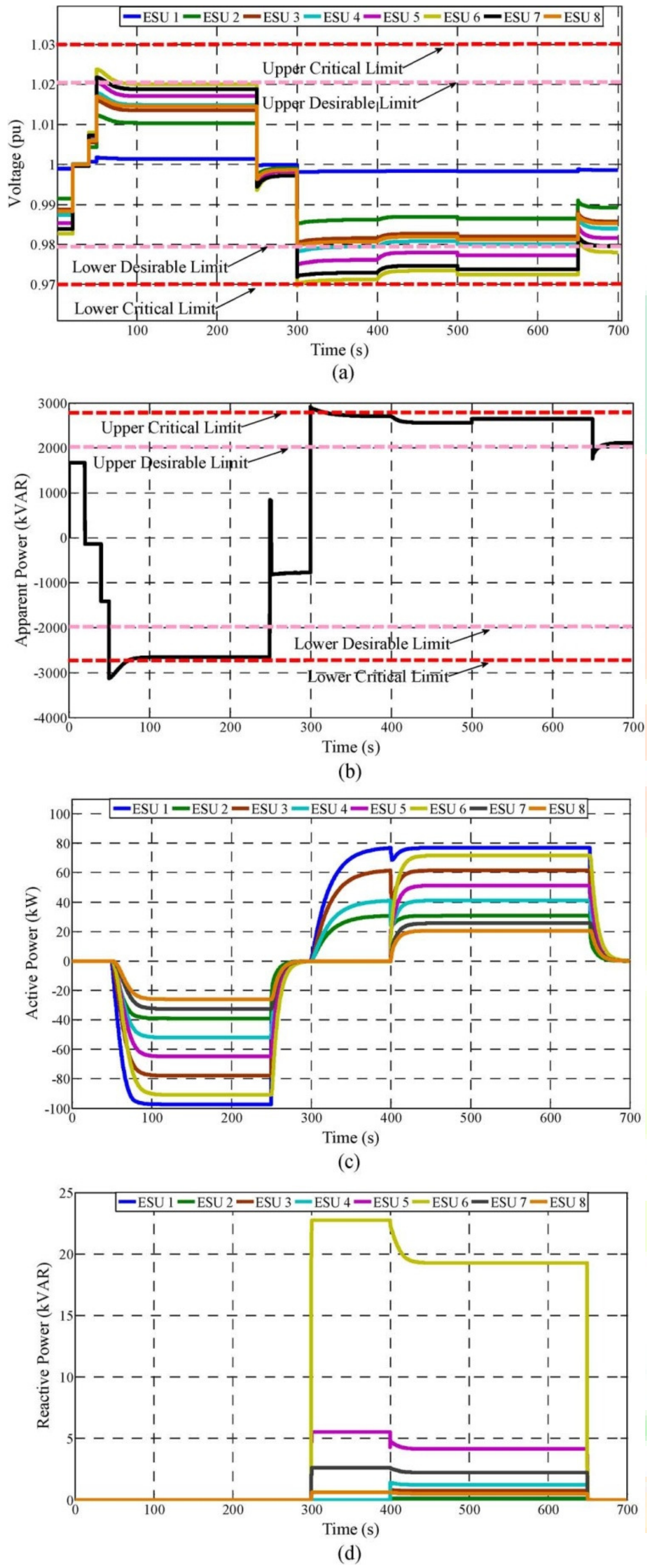

Fig. 9. Proposed control approach with communication drop. (a) ESUs bus voltage.(b)Networkloading.(c)ESUsactivepower.(d)ESUsreactivepower.

5) At 650 s, the network loading and all voltages go to the desirable range. At this point, ESUs stop their contribution for voltage support and network loadingmanagement.

IV. CONCLUSION

This paper proposes a new approach to coordinate multiple ESUs to manage voltage and loading in distribution networks. ESU's active power is used to manage network loading, and ESU reactive power is utilized for voltage support. As the voltage needs fast and robust control, a combined localized and distributed control approach is used to coordinate the ESU re- active power. This method is designed to use the most adjacent ESUs to the violated bus voltage. For loading management, a distributed control strategy based on consensus algorithm is employed to coordinate ESUs' active power. The proposed consensus algorithm has been designed to share the required active power with the same ratio among ESUs with respect to their available active power. This approach has been tested on two systems and the results show that the algorithm works effectively.

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