RESEARCH ARTICLE

A Comprehensive Decomposition Based Hierarchical Heuristic Control of Multimicrogrids

MUHAMMAD ANIQUE ASLAM[1], **SYED ABDUL RAHMAN KASHIF**[1],
GHULAM ABBAS[2], **(Senior Member, IEEE), NASIM ULLAH**[3], **(Member, IEEE),**
LUKAS PROKOP[4], **VOJTECH BLAZEK**[4], **AND STANISLAV MISAK**[4]

[1]Department of Electrical Engineering, University of Engineering and Technology, Lahore 54890, Pakistan
[2]Department of Electrical Engineering, The University of Lahore, Lahore 54000, Pakistan
[3]Department of Electrical Engineering, College of Engineering, Taif University, Taif 21944, Saudi Arabia
[4]ENET Centre, VSB—Technical University of Ostrava, 708 00 Ostrava, Czech Republic

Corresponding authors: Muhammad Anique Aslam (maniqueaslam@uet.edu.pk) and Ghulam Abbas (ghulam.abbas@ee.uol.edu.pk)

ABSTRACT This paper proposes a novel decomposition based hierarchical heuristic control of multimicrogrids to maximize the utilization of renewable energy sources and load satisfaction. The proposed control is capable of providing comprehensive online dispatch of active and reactive powers in steady state modes of operation according to IEEE 2030.7 while keeping in view the restrictions of the participants (microsources and/or microgrids). The proposed solution is generalized to be adopted with respect to different types of participants and grid structures, modular with respect to the number of its participants and capable of protecting the privacy of its participants to maximum possible extent. The proposed heuristic control decomposes the control problem at four levels of hierarchy namely microsource, unit, microgrid and multimicrogrid level. All the distributed energy sources have their own microsource controllers and all the distributed energy sources of the same type are put under one unit controller. All the unit controllers are put under a microgrid controller and all the microgrid controllers are put under a multimicrogrid controller. Information flows from lower to upper levels while dispatch commands flow vice versa. This provides a comprehensive, generic, modular and secure control of a multimicrogrid system. Test cases are simulated to verify the validity of the proposed control scheme.

INDEX TERMS Microgrid, multimicrogrid, multimicrogrid control.

NOMENCLATURE
ACRONYMS

BESS	Battery Based Energy Storage System.
DES	Distributed Energy Source.
ESS	Energy Storage System.
ESSC	Energy Storage System Controller.
ESU	Energy Storage Unit.
LC	Load Controller.

MC	Microsource Controller.
MG	Microgrid.
MGC	Microgrid Controller.
MS	Microsource.
MMG	Multimicrogrid.
MMGC	Multimicrogrid Controller.
MPPT	Maximum Power Point Tracking.
NRES	Non Renewable Energy Source.
NRESC	Non Renewable Energy Source Controller.
POI	Point of Interest.
RES	Renewable Energy Source.

The associate editor coordinating the review of this manuscript and approving it for publication was Salvatore Favuzza.

RESC   Renewable Energy Source Controller.
SoC   State of Charge.
UC   Unit Controller.

VARIABLES

$N_{ess}, N_{nres}, N_{res}$	Total number of energy storage units, non renewable energy sources and renewable energy sources in a microgrid.
$P_{ess,c,rq}, P_{ess,d,rq}, P_{ess,c/d,rq}$	Required active power for charging, discharging and charging or discharging of energy storage units in a microgrid.
$P_{ess,rq}, P_{ess,rq,i}$	Required active power of all the energy storage units and i^{th} energy storage unit in a microgrid.
$P_{l,rq}, P_{l,rq,i}$	Required active load power of a microgrid and i^{th} load in a microgrid.
$P_{ls,rq}, P_{ls,rq,i}$	Required active power load shedding for a microgrid and i^{th} load in a microgrid.
$P_{mg,c,i}, P_{mg,rq,i}$	Coordination and required active power of ith microgrid.
$P_{nres,rq}, P_{nres,rq,i}$	Required active power from non renewable energy sources in a microgrid and i^{th} non renewable energy source in a microgrid.
$P_{res,rq}, P_{res,rq,i}$	Required active power from renewable energy sources in a microgrid and i^{th} renewable energy source in a microgrid.
$Q_{ess,c,rq}, Q_{ess,d,rq}, Q_{ess,c/d,rq}$	Required reactive power for charging, discharging and charging or discharging of energy storage units in a microgrid.
$Q_{ess,rq}, Q_{ess,rq,i}$	Required reactive power of all the energy storage units and i^{th} energy storage unit in a microgrid.
$Q_{l,rq}, Q_{l,rq,i}$	Required reactive load power of a microgrid and i^{th} load in a microgrid.
$Q_{ls,rq}, Q_{ls,rq,i}$	Required reactive power load shedding for a microgrid and i^{th} load in a microgrid.
$Q_{mg,c,i}, Q_{mg,rq,i}$	Coordination and required reactive power of ith microgrid.
$Q_{nres,rq}, Q_{nres,rq,i}$	Required reactive power from non renewable energy sources in a microgrid and i^{th} non renewable energy source in a microgrid.
$Q_{res,rq}, Q_{res,rq,i}$	Required reactive power from renewable energy sources in a microgrid and i^{th} renewable energy source in a microgrid.
$S_{ess,ab}, S_{ess,ab,i}$	Available apparent power from energy storage units in a microgrid and i^{th} energy storage unit in a microgrid.
$S_{ess,c,ab}, S_{ess,d,ab}$	Available charging and discharging power of energy storage units in a microgrid.
$S_{ess,co,ab}, S_{ess,do,ab}, S_{ess,cd,ab}$	Available power of energy storage units in a microgrid that are able to charge only, discharge only and charge and discharge both.
$S_{ess,rq}$	Required apparant power from energy storage units in a microgrid.
$S_{ess,rt,i}$	Rated power of ith energy storage unit.
$S_{mg,ab,i}, S_{mg,ab,nearby}$	Available apparent power of ith microgrid and geographically nearby microgrid.
$S_{nres,ab}, S_{nres,ab,i}$	Available apparant power of non renewable energy sources in a microgrid and i^{th} non renewable energy source in a microgrid.
$S_{nres,rt}, S_{nres,rt,i}$	Rated apparant power of non renewable energy sources in a microgrid and i^{th} non renewable energy source in a microgrid.
$S_{res,ab}, S_{res,ab,i}$	Available apparant power from renewable energy sources in a microgrid and i^{th} renewable energy source in a microgrid.
$S_{nres,rq}, S_{res,rq}$	Required apparant power of non renewable energy sources and renewable energy sources in a microgrid.
SoC_i	State of charge of ith energy storage unit.
$SoC_{ll,i}, SoC_{ul,i}$	Lower and upper limit of state of charge of ith energy storage unit.

I. INTRODUCTION

Renewable Energy Sources (RESs) have emerged as alternatives to solve the economical, environmental and political problems being produced by fossil fuels. But RESs have their own problems like temporal and spatial variations, uncertainty, need of grid integration and electric power transport network, nature of output power, need of an Energy Storage System (ESS) and market viability challenges. These problems can be solved by improving the technology of RESs, using ESSs, integrating RESs with one another and to the traditional grid and devising proper control techniques [1], [2], [3], [4], [5]. Such an integration and control leads to the concept of Microgrid (MG) [6], [7]. A MG is a combination of distributed energy sources, energy storage systems and loads connected to the traditional grid operating as a single entity from the grid point of view

within prescribed electrical boundaries in grid connected and/or islanded mode [6], [7], [8]. That is why MGs are considered as the best option for integrating RESs to the grid and regarded as the building blocks of a smart grid [9], [10]. Its natural to extend the concept of MGs to a Multimicrogrid (MMG) which consists of a number of interconnected MGs [11]. Such a system has marked advantages over a simple MG. As MMGs are the interconnection of many MGs, so, proper control of such a system leads to more flexibility and reliability as compared to individual MGs [12], [13], [14], [15], [16].

The control of MGs can be broadly classified as centralized, decentralized and distributed control [17], [18]. Centralized techniques use a central controller which gives a coordinated control at the cost of high communication and computational requirements increasing with the size of system [19], [20], system level failure due to a single point of failure, data privacy, severe limitations on system modifications [10], general requirement of special solvers [21] and convergence issues [22] and are, therefore, preferred for a system of small size. In decentralized control, each Microsource (MS) is responsible for its own operation based on local measurements without any communication with other MSs [17] leading to severe limitations on system level [10]. Distributed control is in between the two where the participants communicate with one another up to a certain extent but there is no central controller [10], [17]. Hierarchical control is closely related to centralized and distributed control. This control is divided into multiple vertical layers communicating with one another [10], [17]. So, a properly designed hierarchical control can achieve the best of the three discussed techniques. Now a days, the most common approach is heuristic or rule based approach [23] which is simple, quick, less communication and computational intensive and can be verified by human operators leading to high acceptance and less certification issues [21].

Different aspects of MG control using rule based approach are discussed in recent literature. Reference [20] provides a comparison between an optimization and rule based control for offline scheduling. The MG considered consists of solar panels, Battery Based ESS (BESS) and load. A day ahead scheduling is performed. In case of deviation between predicted solar power and load profile, intraday schedules are performed. The basic idea is to compare the solar power and load required at every scheduling instant of time. If the solar power is greater than the load power, it is used to supply the load preferably and then to charge the batteries. Otherwise, power is taken from the grid and/or batteries depending on the cost and load power requirement. Authors showed that such a scheduling algorithm provides the same accuracy as that of centralized optimization algorithms like genetic algorithm and mixed integer linear programming. Reference [21] provides a two step heuristic control for a generic multi bus system based on network information. In the first step, power balance is tried to be achieved for

each bus according to the preset priorities and, if succeeded, power set points of components attached to the particular bus are adjusted based on economical reasons. The number of controllers grow proportionally with respect to the number of buses. Moreover, there can be some cases where no solution exists. Reference [24] presents a hybrid control to provide battery set points for a so called end user MG consisting of PV integrated battery and a controllable load. An end user MG is limited to share power with the utility only. In grid connected mode, dynamic programming based moving horizon control is used while a rule based control is applied in islanded mode. In case of islanded mode of operation, the rule based control calculates the power of the battery. After that, the State of Charge (SoC) is calculated and power is dispatched keeping in view its power limits. Load is also controlled based on the time of the day, SoC, and voltage at the point of common coupling. Methodologies for disconnection and reconnection of MG to the utility are proposed. An aggregator to maintain power balance for single and three phase MGs is proposed. Reference [25] presents a power sharing method for a hybrid ESS consisting of batteries and super capacitors to mitigate the frequency deviations. A hybrid approach derived from low pass filtering method and a rule based method is proposed. In low pass filtering approach, low pass component of the reference power is considered as reference for the batteries and high pass component as reference for the super capacitors. Generally, in rule based approach, reference power is first assigned to the super capacitor as such or as a function of the voltage and the left over power is assigned to batteries keeping in view the voltage and power limits of the components. The proposed approach first filters the reference power to low and high frequency parts. The high frequency part is assigned to super capacitor in priority keeping in view its voltage and power constraints. The left over high frequency power, if any, along with low frequency power is assigned to the batteries. Simulation results validate the positive impact of these control techniques on mitigation of frequency deviations. More details on mitigation of frequency deviations in MMGs can be found in [26], [27], and [28]. The control techniques should be able to maintain the voltage and current parameters in a range that satisfy the standards [29], [30], [31]. Reference [32] provides a similar rule based approach for hybrid ESS integrated with RESs. Reference [33] presents a rule based approach to manage critical and non-critical loads for a stand alone PV based BESS in order to maximize the penetration of RESs. Reference [34] presents a rule based control of a residential MG consisting of solar panels, stationary batteries, programmable electronic load emulating demand side management and a plug in electric vehicle. A charger/inverter is used which can take power from four different sources (i.e. PV, batteries, electric vehicle (during discharging) and grid) and supply power to the load and electric vehicle (during charging). There are three relays. First relay is connected between grid and charger/inverter. Second relay is in the discharging path and the third relay

in the charging path of the electric vehicle. The aim is to reduce the power taken from the grid for a particular load. If PV power is greater than the load, extra power is used to charge the batteries. If there is still some power left, it can be used to charge the electric vehicle if needed. The remaining power, if any, is used as feed in. If PV power is not greater than the load, extra power is taken by discharging the batteries if it can be done. The remaining power, if any, is taken from the grid. This control scheme does not schedule the power. It just switches the relays for a residential MG. Reference [23] compares the rule based control and optimization based control of a particular MG testbed in CANREL which consists of RESs (solar and wind), BESS and two diesel generators. There are six states of MG. State 1 is the initial state when the control starts. In this state, BESS is responsible to meet the demands. In case of low SoC limits or high power demands, the control switches the first diesel generator (state 2) or the second diesel generator (state 3) or both (state 4) depending on the power demand. There can be back transitions depending on power demand, costs of the generator/s and SoC of the BESS. Control can shut down some load (state 6) if the load cannot be fulfilled even by turning on both the generators (state 4). Curtailment of RESs occur (state 6) if their power exceeds even after being used for charging the BESS and supplying the load. Reference [35] describes a centralized rule based control for a MG based on three SoC ranges of a BESS. Reference [22] extends the same control strategy to facilitate plug and play capacity of a Distributed Energy Source (DES). Reference [36] describes a rule based control in accordance with the IEEE 2030.7 standard [37]. This strategy is similar to [35] except the diesel generator is not dispatchable in grid tie mode while it can be dispatched in islanded mode. Load management is deployed to shed and restore the loads according to their criticality and controlability. Reference [38] presents a general rule based control applied to rural MGs in Venezuela. Reference [39] describes a rule based approach for a DC MG consisting of solar panels, wind, ESS and AC loads for islanded DC MGs. ESS is charged or discharged if generation is higher or lower as compared to the load respectively. Generation from RESs is curtailed if the battery is fully charged and the load demand is satisfied. Load is shedded if power from discharging RESs and ESS is not enough to satisfy the loads.

It is clear from the above discussion that each rule based control strategy is quite simple lacking one or more among the elements of operational comprehensiveness, generality, modularity and privacy. Keeping this in view, a new decomposition based hierarchical heuristic MMG control system is proposed with following features.

- Provision of novel comprehensive online dispatch functions for active and reactive power flow control in steady state modes of operation (grid connected and islanded) in compliance with IEEE 2030.7 to maximize the penetration of RESs and load satisfaction

- Generality with respect to types of participants and network structure
- Modularity with respect to the number of MSs and MGs
- Privacy i.e. minimum possible exchange of information

To the best knowledge of authors, such a comprehensive, generic, modular and secure rule based approach for MMG control which is hierarchical, dynamic and decomposable in nature is not proposed yet.

The rest of the paper is organized as follows. Section II describes the theoretical framework to develop the proposed control strategy. Section III discusses the behavior of controllers at different levels of hierarchy. Finally, Section IV concludes and states some points for future work.

II. THEORETICAL FRAMEWORK AND DEVELOPMENT OF CONTROL STRATEGY

For devising a control technique as discussed in Section I, a number of MGs are considered to be connected to the traditional grid at the Point of Interest (POI) as shown in Fig. 1. Each MG consists of a number of RESs, Energy Storage Units (ESUs), Non Renewable Energy Sources (NRESs) and loads. Each DES has its own controller called Microsource Controller (MC). All the DESs of the same type are controlled by a Unit Controller (UC). So, there are four UCs in a MG namely RES Controller (RESC), ESS Controller (ESSC), NRES Controller (NRESC) and Load Controller (LC). All these UCs in a MG are controlled by a MG Controller (MGC). Different MGCs are controlled by a MMG Controller (MMGC). The objective is to maximize the load satisfaction with maximum possible penetration of RESs by devising a control scheme that provides online dispatch functions, generic with respect to the types of microsources and microgrids, applicable when the number of microsources or microgrids varies and relies on minimum possible information exchange. To achieve these objectives, a hierarchical control structure is designed in such a way that the control problem is decomposed into sub problems which can be solved by the lower level controllers. This reduces computational and communication requirements as compared to centralized techniques while providing a reliable and coordinated operation as compared to distributed techniques. The controllers at each level are designed in such a way that they only require information about the power requirement and constraints from the lower controllers without requiring any information about the nature of DESs being controlled at lower levels. A heuristic or rule based approach is adopted as it is common, simple, quick, less communication and computational intensive and can be verified by human operators leading to high acceptance and less certification issues. The control algorithms of these controllers are described below.

A. MULTIMICROGRID CONTROLLER (MMGC)

At the top, there is MMGC which takes the available apparent power ($S_{mg,ab,i}$), required active ($P_{mg,rq,i}$) and reactive ($Q_{mg,rq,i}$) power from each MG and distributes the
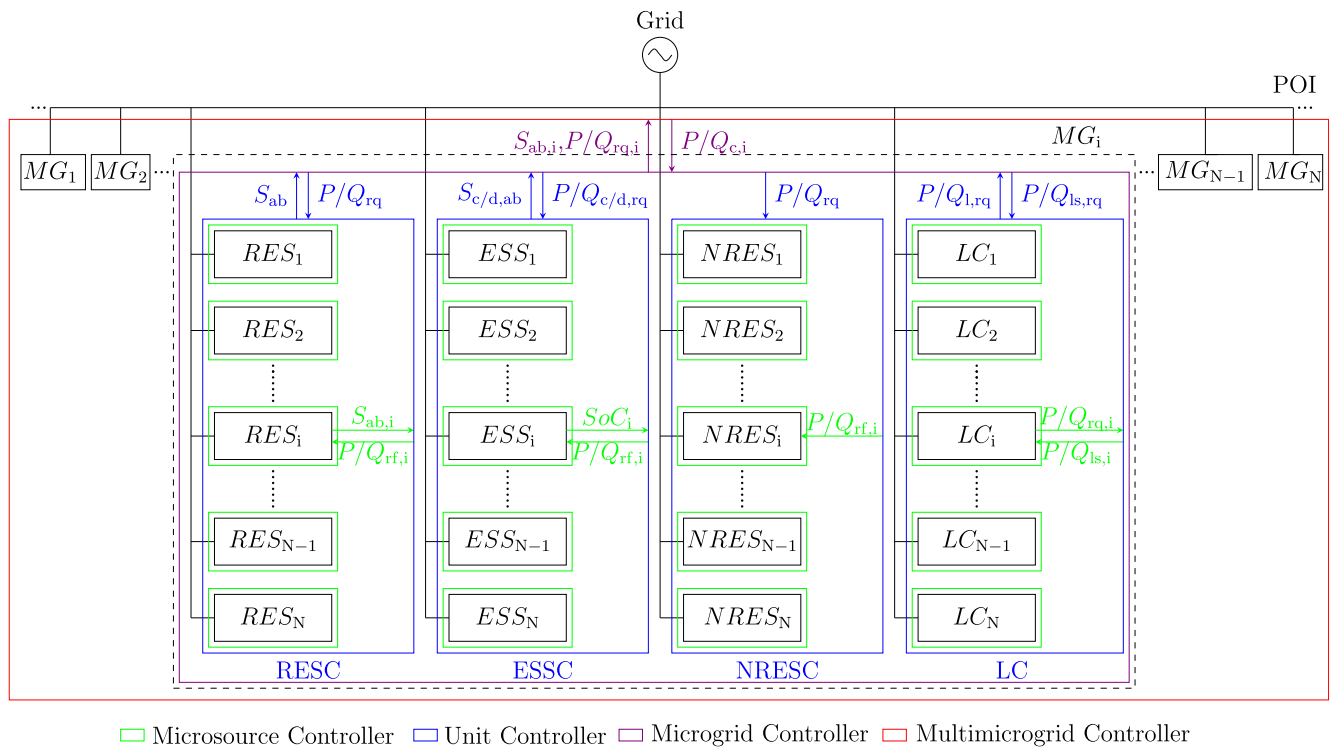
FIGURE 1. Schematic diagram of the proposed control hierarchy. MMGC is at the top to control the power flows among the associated microgrids. Each microgrid has its own MGC which controls different UCs. There are four UCs namely RESC, ESSC, NRESC and LC. Each UC has DESs of the same kind grouped together. Each DES has its own controller called MC. Information about power capacity and requirement flows from lower to immediate higher hierarchical controller while the dispatch commands flow vice versa.

geographically nearby available capacity to the deserving MGs by dispatching respective active ($P_{mg,c,i}$) and reactive ($Q_{mg,c,i}$) coordination powers according to Algorithm 1. MMGC checks each MG one by one and if power is required for a particular MG, MMGC checks the available capacity of its nearby MG ($S_{mg,ab,nearby}$). Here two scenarios arise.

- If $S_{mg,ab,nearby}$ is sufficient to meet the entire needs of the MG under consideration, the required portion of the $S_{mg,ab,nearby}$ is allocated to the MG under consideration.
- If $S_{mg,ab,nearby}$ is not sufficient to meet the entire needs of the MG under consideration, entire $S_{mg,ab,nearby}$ is allocated to the MG under consideration. There are three scenarios here.
  - If only the active power is required, the whole of $S_{mg,ab,nearby}$ is allocated as $P_{mg,c,i}$.
  - If only the reactive power is required, the whole of $S_{mg,ab,nearby}$ is allocated as $Q_{mg,c,i}$.
  - If both the active and reactive powers are required, MMGC allocates $S_{mg,ab,nearby}$ to $P_{mg,c,i}$ and $Q_{mg,c,i}$ according to the ratios of their power factors using Eq. 1 and Eq. 2.

$$P_{mg,c,i} = S_{mg,ab,nearby} \times \frac{1}{\sqrt{1 + (\frac{Q_{mg,rq,i}}{P_{mg,rq,i}})^2}} \quad (1)$$

$$Q_{mg,c,i} = S_{mg,ab,nearby} \times \frac{1}{\sqrt{1 + (\frac{P_{mg,rq,i}}{Q_{mg,rq,i}})^2}} \quad (2)$$

In this way, the MMGC goes to the other nearby MGs until the demand of the MG under consideration is met or there is no MG left to supply it.

B. MICROGRID CONTROLLER (MGC)

MGC takes the available apparent power from RESs ($S_{res,ab}$) through RESC, total available power of the units that are able to charge only ($S_{ess,co,ab}$), total available power of the units that are able to discharge only ($S_{ess,do,ab}$) and total available power of the units that are able to charge and discharge both ($S_{ess,cd,ab}$) from ESSC, total rated power of NRESs ($S_{nres,rt}$) from NRESC and the required active ($P_{l,rq}$) and reactive ($Q_{l,rq}$) load power from LC. It dispatches the required active and reactive power commands to the respective UCs (see Algorithm 2). Following scenarios arise in case of grid connected mode of operation.

- If reactive power required is zero, $P_{res,rq}$ is considered equal to $S_{res,ab}$. By having so, we make sure maximum utilization of RESs. ESUs are charged to the maximum extent by taking $P_{ess,c,rq}$ equal to $S_{ess,c,ab}$ to maximize load satisfaction during islanded events.
- If the reactive power required is greater than zero and $S_{res,ab} > Q_{l,rq}$, $Q_{res,rq}$ is set equal to $Q_{l,rq}$.

Algorithm 1: Proposed Algorithm for MMGC

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for *check each microgrid* **do**
    if *active and/or reactive power is required* **then**
        for *check nearby microgrid* **do**
            if $S_{mg,ab,nearby} \geq S_{mg,rq,i}$ **then**
                $P_{mg,c,i} = P_{mg,rq,i}$
                $Q_{mg,c,i} = Q_{mg,rq,i}$
            else if $Q_{mg,rq,i} = 0$ **then**
                $P_{mg,c,i} = S_{mg,ab,nearby}$
            else if $P_{mg,rq,i} = 0$ **then**
                $Q_{mg,c,i} = S_{mg,ab,nearby}$
            else
                $P_{mg,c,i} = S_{mg,ab,nearby} \times \dfrac{1}{\sqrt{1+(\frac{Q_{mg,rq,i}}{P_{mg,rq,i}})^2}}$
                $Q_{mg,c,i} = S_{mg,ab,nearby} \times \dfrac{1}{\sqrt{1+(\frac{P_{mg,rq,i}}{Q_{mg,rq,i}})^2}}$
            end
        end
    end
end

If $S_{res,ab} < Q_{l,rq}$, $Q_{res,rq}$ is set equal to $S_{res,ab}$. The remaining reactive power required ($Q_{l,rq} - Q_{res,rq}$) is set equal to $Q_{ess,d,rq}$ if it is less than $S_{ess,d,ab}$. Otherwise, $Q_{ess,d,rq}$ is set equal to $S_{ess,d,ab}$. The reactive power still remaining ($Q_{l,rq} - Q_{res,rq} - Q_{ess,d,rq}$) is taken from NRES if it is less than $S_{nres,rt}$ by setting it equal to $Q_{nres,rq}$. Otherwise, NRES are scheduled at their full capacity and the remaining reactive power ($Q_{l,rq} - Q_{res,rq} - Q_{ess,d,rq} - Q_{nres,rq}$) will be contributed by the grid. After scheduling the reactive power, the available powers from RESs and ESUs are updated and $P_{res,rq}$ is set equal to $S_{res,ab}$ and ESUs are charged at the remaining capacity.

- If the reactive power required is less than zero, the reactive power is absorbed by ESUs as much as possible. The rest is contributed by the grid. After scheduling the reactive power, the available powers from RESs and ESUs are updated and $P_{res,rq}$ is set equal to $S_{res,ab}$ and ESUs are charged at the remaining capacity.

Following scenarios arise in case of islanded mode of operation.

- If the reactive power required is equal to zero and $S_{res,ab} > P_{l,rq}$, $P_{res,rq}$ is set equal to $P_{l,rq}$ i.e. the load of the MG will be supplied by the RESs exclusively. The remaining power ($S_{res,ab} - P_{l,rq}$) is set equal to $P_{ess,c,rq}$ if it is less than $S_{ess,c,ab}$. Otherwise, $P_{ess,c,rq}$ is set equal to $S_{ess,c,ab}$ and the excess RES energy (i.e. $S_{res,ab} - P_{l,rq} - P_{ess,c,rq}$) is curtailed. If $S_{res,ab} < P_{l,rq}$, $P_{res,rq}$ is set equal to $S_{res,ab}$. The remaining load power required ($P_{l,rq} - P_{res,rq}$) is set equal to $P_{ess,d,rq}$ if it is less than $S_{ess,d,ab}$. Otherwise, $P_{ess,d,rq}$ is set equal to $S_{ess,d,ab}$ and the remaining load power ($P_{l,rq} - P_{res,rq} - P_{ess,d,rq}$) is taken from NRESs if it is less than $S_{nres,rt}$ by setting it equal to $P_{nres,rq}$. Otherwise, NRESs are

scheduled at their full capacity and the remaining load ($P_{l,rq} - P_{res,rq} - P_{ess,d,rq} - P_{nres,rq}$) is shedded.

- If the reactive power required is greater than zero and $S_{res,ab} > Q_{l,rq}$, $Q_{res,rq}$ is set equal to $Q_{l,rq}$. If $S_{res,ab} < Q_{l,rq}$, $Q_{res,rq}$ is set equal to $S_{res,ab}$. The remaining reactive power required ($Q_{l,rq} - Q_{res,rq}$) is set equal to $Q_{ess,d,rq}$ if it is less than $S_{ess,d,ab}$. Otherwise, $Q_{ess,d,rq}$ is set equal to $S_{ess,d,ab}$. The reactive power still remaining ($Q_{l,rq} - Q_{res,rq} - Q_{ess,d,rq}$) is taken from NRESs if it is less than $S_{nres,rt}$ by setting it equal to $Q_{nres,rq}$. Otherwise, NRESs are scheduled at their full capacity and the remaining reactive power ($Q_{l,rq} - Q_{res,rq} - Q_{ess,d,rq} - Q_{nres,rq}$) is shedded. After scheduling the reactive power, the available powers from RESs, ESUs and NRESs are updated and the active power is scheduled similar to the case when the reactive power required is equal to zero.

- If the reactive power required is less than zero, the reactive power is absorbed by ESUs as much as possible. The rest is shedded. After scheduling the reactive power, the available powers from RESs, ESUs and NRESs are updated and the active power is scheduled similar to the case when the reactive power required is equal to zero.

Algorithm 2: Proposed Algorithm for MGC

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if *grid connected* **then**
    if $Q_{l,rq} = 0$ **then**
        Operate RESs at maximum power point.
        Charge ESUs to maximum extent.
    else if $Q_{l,rq} > 0$ **then**
        Use RESs, ESUs and NRESs in order to supply $Q_{l,rq}$. The rest, if any, will come from grid.
        Perform the active power scheduling as in case of $Q_{l,rq} = 0$.
    else if $Q_{l,rq} < 0$ **then**
        Use ESUs to absorb $Q_{l,rq}$. The rest, if any, will be compensated by grid.
        Perform the active power scheduling as in case of $Q_{l,rq} = 0$.
    end
else
    if $Q_{l,rq} = 0$ **then**
        Use RESs, ESSs and NRESs in order to supply $P_{l,rq}$ and shed the rest, if any.
        Charge ESUs from RESs if possible and curtail RESs if required.
    else if $Q_{l,rq} > 0$ **then**
        Use RESs, ESUs and NRESs to supply $Q_{l,rq}$ and shed the rest, if any.
        Perform the active power scheduling as in case of $Q_{l,rq} = 0$.
    else if $Q_{l,rq} < 0$ **then**
        Use ESUs to absorb $Q_{l,rq}$. The rest, if any, will be shedded.
        Perform the active power scheduling as in case of $Q_{l,rq} = 0$.
    end
end

C. RENEWABLE ENERGY SOURCES CONTROLLER (RESC)

RESC conveys total available power from all the RESs ($S_{\text{res,ab}}$) to the MGC and takes the required active ($P_{\text{res,rq}}$) and reactive ($Q_{\text{res,rq}}$) power from it. The information about the total number of RESs (N_{res}) and available power of each individual RES ($S_{\text{res,ab,i}}$) is available from the respective MC. It dispatches the required active and reactive power commands to the MC of each RES according to the Algorithm 3. Following cases are considered.

- If only the active or reactive power is required, the RESC turns on RESs one by one in a specified order to operate in Maximum Power Point Tracking (MPPT) mode. If the MPPT power of a particular unit is greater than the required power, the unit is operated at the reduced power and the other units are turned off.

- If both active and reactive powers are required, the RESC distributes the required power to all the MCs according to a uniform ratio ($\frac{S_{\text{res,rq}}}{S_{\text{res,ab}}}$) in such a way that all the MCs provide active and reactive power with a power factor that corresponds to the power factor of the active and reactive powers required from a particular MC of a RES at that time. This can be achieved by using Eq. 3 and Eq. 4.

$$P_{\text{res,rq,i}} = \frac{S_{\text{res,rq}}}{S_{\text{res,ab}}} \times S_{\text{res,ab,i}} \times \frac{1}{\sqrt{1+(\frac{Q_{\text{res,rq}}}{P_{\text{res,rq}}})^2}} \quad (3)$$

$$Q_{\text{res,rq,i}} = \frac{S_{\text{res,rq}}}{S_{\text{res,ab}}} \times S_{\text{res,ab,i}} \times \frac{1}{\sqrt{1+(\frac{P_{\text{res,rq}}}{Q_{\text{res,rq}}})^2}} \quad (4)$$

Algorithm 3: Proposed Algorithm for RESC

if $P_{\text{res,rq}} > 0$ *or* $Q_{\text{res,rq}} > 0$ **then**

    for *1:N_{res}* **do**

        Turn on the unit at maximum power point.

        Update the required power.

        If the required power is met, turn off other units.

        If the required power is negative, operate the current unit at reduced power and turn off other units.

    end

else if *both active and reactive powers are required* **then**

    $S_{\text{res,rq}} = \sqrt{(P_{\text{res,rq}})^2 + (Q_{\text{res,rq}})^2}$

    for *1:N_{res}* **do**

        $P_{\text{res,rq,i}} = \frac{S_{\text{res,rq}}}{S_{\text{res,ab}}} \times S_{\text{res,ab,i}} \times \frac{1}{\sqrt{1+(\frac{Q_{\text{res,rq}}}{P_{\text{res,rq}}})^2}}$

        $Q_{\text{res,rq,i}} = \frac{S_{\text{res,rq}}}{S_{\text{res,ab}}} \times S_{\text{res,ab,i}} \times \frac{1}{\sqrt{1+(\frac{P_{\text{res,rq}}}{Q_{\text{res,rq}}})^2}}$

    end

end

D. ENERGY STORAGE SYSTEM CONTROLLER (ESSC)

ESSC takes the SoC of each ESU (SoC_i) from the respective MC. Rated apparent power ($S_{\text{ess,rt,i}}$), upper ($SoC_{\text{ul,i}}$) and lower ($SoC_{\text{ll,i}}$) limits of SoC of each ESU are specified from the owner. Based on the SoC status of each ESU, ESSC calculates $S_{\text{ess,co,ab}}$, $S_{\text{ess,do,ab}}$ and $S_{\text{ess,cd,ab}}$ for MGC. The MGC communicates required active and reactive charging and discharging powers ($P_{\text{ess,c,rq}}, P_{\text{ess,d,rq}}, Q_{\text{ess,c,rq}}, Q_{\text{ess,d,rq}}$) to ESSC. Based on these requirements, the ESSC dispatches the active ($P_{\text{ess,rq,i}}$) and reactive ($Q_{\text{ess,rq,i}}$) power references to each ESU based on following scenarios (see Algorithm 4).

- Only active or reactive power is required i.e $P_{\text{ess,c,rq}} > 0$ or $P_{\text{ess,d,rq}} > 0$ or $Q_{\text{ess,c,rq}} > 0$ or $Q_{\text{ess,d,rq}} > 0$

  - If only $P_{\text{ess,c,rq}} > 0$, ESSC sets $P_{\text{ess,rq,i}} = S_{\text{ess,rt,i}}$ one by one according to the owner specified preference as long as $P_{\text{ess,c,rq}} > S_{\text{ess,rt,i}}$ and $SoC_i < SoC_{\text{ul,i}}$. The unit for which $P_{\text{ess,c,rq}} \leq S_{\text{ess,rt,i}}$ and $SoC_i < SoC_{\text{ul,i}}$ is set at the leftover $P_{\text{ess,c,rq}}$ and the other units are undispatched as $P_{\text{ess,c,rq}}$ is achieved.

  - If only $P_{\text{ess,d,rq}} > 0$, ESSC sets $P_{\text{ess,rq,i}} = -S_{\text{ess,rt,i}}$ one by one according to the owner specified preference as long as $P_{\text{ess,d,rq}} > S_{\text{ess,rt,i}}$ and $SoC_i > SoC_{\text{ll,i}}$. The unit for which $P_{\text{ess,d,rq}} \leq S_{\text{ess,rt,i}}$ and $SoC_i > SoC_{\text{ll,i}}$ is set at the leftover $P_{\text{ess,d,rq}}$ and the other units are undispatched as $P_{\text{ess,d,rq}}$ is achieved.

  - If only $Q_{\text{ess,c,rq}} > 0$, ESSC sets $Q_{\text{ess,rq,i}} = S_{\text{ess,rt,i}}$ one by one according to the owner specified preference as long as $Q_{\text{ess,c,rq}} > S_{\text{ess,rt,i}}$ and $SoC_i < SoC_{\text{ul,i}}$. The unit for which $Q_{\text{ess,c,rq}} \leq S_{\text{ess,rt,i}}$ and $SoC_i < SoC_{\text{ul,i}}$ is set at the leftover $Q_{\text{ess,c,rq}}$ and the other units are undispatched as $Q_{\text{ess,c,rq}}$ is achieved.

  - If only $Q_{\text{ess,d,rq}} > 0$, ESSC sets $Q_{\text{ess,rq,i}} = -S_{\text{ess,rt,i}}$ one by one according to the owner specified preference as long as $Q_{\text{ess,d,rq}} > S_{\text{ess,rt,i}}$ and $SoC_i > SoC_{\text{ll,i}}$. The unit for which $Q_{\text{ess,d,rq}} \leq S_{\text{ess,rt,i}}$ and $SoC_i > SoC_{\text{ll,i}}$ is set at the leftover $Q_{\text{ess,d,rq}}$ and the other units are undispatched as $Q_{\text{ess,d,rq}}$ is achieved.

- Only charging or discharging powers are required i.e. ($P_{\text{ess,c,rq}} > 0$ & $Q_{\text{ess,c,rq}} > 0$) or ($P_{\text{ess,d,rq}} > 0$ & $Q_{\text{ess,d,rq}} > 0$)

  - If $P_{\text{ess,c,rq}} > 0$ and $Q_{\text{ess,c,rq}} > 0$, ESSC calculates the required power ($S_{\text{ess,rq}}$) by using Eq. 5. $S_{\text{ess,rq}}$ is met by dispatching the ESUs according to Eq. 6 and Eq. 7. The factor $\frac{S_{\text{ess,rq}}}{S_{\text{ess,ab}}}$ ensures that all the ESUs contribute in equal proportion towards meeting $S_{\text{ess,rq}}$ whereas the factors $\frac{1}{\sqrt{1+(\frac{Q_{\text{ess,rq}}}{P_{\text{ess,rq}}})^2}}$ and $\frac{1}{\sqrt{1+(\frac{P_{\text{ess,rq}}}{Q_{\text{ess,rq}}})^2}}$ draw active and reactive power from $S_{\text{ess,ab,i}}$ at a power factor equal to the power factor of $P_{\text{ess,c,rq}}$ and $Q_{\text{ess,c,rq}}$ at that time.

$$S_{\text{ess,rq}} = \sqrt{(P_{\text{ess,c,rq}})^2 + (Q_{\text{ess,c,rq}})^2} \quad (5)$$

$$P_{\text{ess,rq,i}} = \frac{S_{\text{ess,rq}}}{S_{\text{ess,ab}}} \times S_{\text{ess,ab,i}} \times \frac{1}{\sqrt{1+(\frac{Q_{\text{ess,rq}}}{P_{\text{ess,rq}}})^2}} \quad (6)$$

$$Q_{\text{ess,rq,i}} = \frac{S_{\text{ess,rq}}}{S_{\text{ess,ab}}} \times S_{\text{ess,ab,i}} \times \frac{1}{\sqrt{1+(\frac{P_{\text{ess,rq}}}{Q_{\text{ess,rq}}})^2}} \quad (7)$$

- If $P_{\text{ess,d,rq}} > 0$ and $Q_{\text{ess,d,rq}} > 0$, ESSC calculates the required power ($S_{\text{ess,rq}}$) by using Eq. 8. $S_{\text{ess,rq}}$ is met by dispatching the ESUs according to Eq. 9 and Eq. 10 which resemble Eq. 6 and Eq. 7 respectively with the exception of sign reversal as the ESUs are required to discharge in this case.

$$S_{\text{ess,rq}} = \sqrt{(P_{\text{ess,d,rq}})^2 + (Q_{\text{ess,d,rq}})^2} \qquad (8)$$

$$P_{\text{ess,rq,i}} = -\frac{S_{\text{ess,rq}}}{S_{\text{ess,ab}}} \times S_{\text{ess,ab,i}} \times \frac{1}{\sqrt{1 + (\frac{Q_{\text{ess,rq}}}{P_{\text{ess,rq}}})^2}} \qquad (9)$$

$$Q_{\text{ess,rq,i}} = -\frac{S_{\text{ess,rq}}}{S_{\text{ess,ab}}} \times S_{\text{ess,ab,i}} \times \frac{1}{\sqrt{1 + (\frac{P_{\text{ess,rq}}}{Q_{\text{ess,rq}}})^2}} \qquad (10)$$

- Both charging and discharging powers are required i.e. ($P_{\text{ess,c,rq}} > 0$ & $Q_{\text{ess,d,rq}} > 0$) or ($P_{\text{ess,d,rq}} > 0$ & $Q_{\text{ess,c,rq}} > 0$)
  - If $P_{\text{ess,c,rq}} > 0$ and $Q_{\text{ess,d,rq}} > 0$, ESSC first charges the units capable of charging only by setting $P_{\text{ess,rq,i}} = S_{\text{ess,rt,i}}$ one by one according to the owner specified preference as long as $P_{\text{ess,c,rq}} > S_{\text{ess,rt,i}}$ and $SoC_i < SoC_{\text{ll,i}}$. The unit, if any, for which $P_{\text{ess,c,rq}} \leq S_{\text{ess,rt,i}}$ and $SoC_i < SoC_{\text{ll,i}}$ is set at the leftover $P_{\text{ess,c,rq}}$ and the other charge only units are undispatched as $P_{\text{ess,c,rq}}$ is achieved. If $P_{\text{ess,c,rq}}$ is not met, it will come from the units that are capable of bidirectional operation. After that, the units capable of discharging only are discharged by setting $Q_{\text{ess,rq,i}} = -S_{\text{ess,rt,i}}$ one by one according to the owner specified preference as long as $Q_{\text{ess,d,rq}} > S_{\text{ess,rt,i}}$ and $SoC_i > SoC_{\text{ul,i}}$. The unit, if any, for which $Q_{\text{ess,d,rq}} \leq S_{\text{ess,rt,i}}$ and $SoC_i > SoC_{\text{ul,i}}$ is set at the leftover $Q_{\text{ess,d,rq}}$ and the other discharge only units are undispatched as $Q_{\text{ess,d,rq}}$ is achieved. If $Q_{\text{ess,d,rq}}$ is not met, it will come from the units that are capable of bidirectional operation. After utilizing the units capable of unidirectional operation, the remaining $S_{\text{ess,rq}}$ is calculated using Eq. 11 and dispatched according to Eq. 12 and Eq. 13.

$$S_{\text{ess,rq}} = \sqrt{(P_{\text{ess,c,rq}})^2 + (Q_{\text{ess,d,rq}})^2} \qquad (11)$$

$$P_{\text{ess,rq,i}} = \frac{S_{\text{ess,rq}}}{S_{\text{ess,cd,ab}}} \times S_{\text{ess,ab,i}} \times \frac{1}{\sqrt{1 + (\frac{Q_{\text{ess,rq}}}{P_{\text{ess,rq}}})^2}} \qquad (12)$$

$$Q_{\text{ess,rq,i}} = -\frac{S_{\text{ess,rq}}}{S_{\text{ess,cd,ab}}} \times S_{\text{ess,ab,i}} \times \frac{1}{\sqrt{1 + (\frac{P_{\text{ess,rq}}}{Q_{\text{ess,rq}}})^2}} \qquad (13)$$

Eq. 12 and Eq. 13 resemble Eq. 6 and Eq. 7 respectively with the exception that $S_{\text{ess,cd,ab}}$ is used instead of $S_{\text{ess,ab}}$ as we are dispatching the units capable of charging and discharging.

- If $P_{\text{ess,d,rq}} > 0$ and $Q_{\text{ess,c,rq}} > 0$, ESSC first charges the units capable of charging only by setting $Q_{\text{ess,rq,i}} = S_{\text{ess,rt,i}}$ one by one according to the owner specified preference as long as $Q_{\text{ess,c,rq}} > S_{\text{ess,rt,i}}$ and $SoC_i < SoC_{\text{ll,i}}$ until $Q_{\text{ess,c,rq}}$ is met or there is no ESU left that is capable of charging only. After that, the units capable of discharging only are discharged by setting $P_{\text{ess,rq,i}} = -S_{\text{ess,rt,i}}$ one by one according to the owner specified preference as long as $P_{\text{ess,d,rq}} > S_{\text{ess,rt,i}}$ and $SoC_i > SoC_{\text{ul,i}}$ until $P_{\text{ess,d,rq}}$ is met or there is no ESU left that is capable of discharging only. The remaining $S_{\text{ess,rq}}$ is calculated using Eq. 14 and dispatched according to Eq. 15 and Eq. 16 for the units that are capable of bidirectional operation.

$$S_{\text{ess,rq}} = \sqrt{(P_{\text{ess,d,rq}})^2 + (Q_{\text{ess,c,rq}})^2} \qquad (14)$$

$$P_{\text{ess,rq,i}} = -\frac{S_{\text{ess,rq}}}{S_{\text{ess,cd,ab}}} \times S_{\text{ess,ab,i}} \times \frac{1}{\sqrt{1 + (\frac{Q_{\text{ess,rq}}}{P_{\text{ess,rq}}})^2}} \qquad (15)$$

$$Q_{\text{ess,rq,i}} = \frac{S_{\text{ess,rq}}}{S_{\text{ess,cd,ab}}} \times S_{\text{ess,ab,i}} \times \frac{1}{\sqrt{1 + (\frac{P_{\text{ess,rq}}}{Q_{\text{ess,rq}}})^2}} \qquad (16)$$

Eq. 15 and Eq. 16 resemble Eq. 12 and Eq. 13 respectively with the exception of sign reversals.

E. NON RENEWABLE ENERGY SOURCE CONTROLLER (NRESC)

NRESC takes the required active ($P_{\text{nres,rq}}$) and reactive ($Q_{\text{nres,rq}}$) power from MGC. The information about the total number of NRESs (N_{nres}) and rated apparent power of each individual NRES ($S_{\text{nres,rt,i}}$) is available from the owner. It dispatches the required active and reactive power commands to the respective MCs according to Algorithm 5 which consists of following rules.

- If only the active or reactive power is required, the NRESC turns on NRESs one by one in a prespecified order. If the power of a particular unit is greater than the required power, the unit is operated at the reduced power and the other units are turned off.
- If both active and reactive powers are required, the NRESC distributes the required active and reactive powers among the participating units in such a way that all units participate equally in proportion to their installed capacities (ensured by the factor $\frac{S_{\text{nres,rq}}}{S_{\text{nres,ab}}}$) while maintaining a power factor equal to the power factor required at that time (ensured by the factors $\frac{1}{\sqrt{1+(\frac{Q_{\text{nres,rq}}}{P_{\text{nres,rq}}})^2}}$ and $\frac{1}{\sqrt{1+(\frac{P_{\text{nres,rq}}}{Q_{\text{nres,rq}}})^2}}$ for active and reactive powers resectively) according to Eq. 17 and Eq. 18.

$$P_{\text{nres,rq,i}} = \frac{S_{\text{nres,rq}}}{S_{\text{nres,ab}}} \times S_{\text{nres,ab,i}} \times \frac{1}{\sqrt{1 + (\frac{Q_{\text{nres,rq}}}{P_{\text{nres,rq}}})^2}} \qquad (17)$$

Algorithm 4: Proposed Algorithm for ESSC

if *only* $P_{ess,c,rq} > 0$ *or* $P_{ess,d,rq} > 0$ *or* $Q_{ess,c,rq} > 0$ *or* $Q_{ess,d,rq} > 0$ **then**

 Turn on the unit at its rated power depending on its SoC.

 Update the required power.

 If the required power is met, turn off other units.

 If the required power is negative, operate the current unit at reduced power and turn off other units.

else if *(*$P_{ess,c,rq} > 0$ *&* $Q_{ess,c,rq} > 0$*) or (*$P_{ess,d,rq} > 0$ *&* $Q_{ess,d,rq} > 0$*)* **then**

$$S_{ess,rq} = \sqrt{(P_{ess,c/d,rq})^2 + (Q_{ess,c/d,rq})^2}$$

 for *1:N_{ess}* **do**

  if *SoC conditions are met* **then**

$$P_{ess,rq,i} = \pm \frac{S_{ess,rq}}{S_{ess,ab}} \times S_{ess,ab,i} \times \frac{1}{\sqrt{1+(\frac{Q_{ess,rq}}{P_{ess,rq}})^2}}$$

$$Q_{ess,rq,i} = \pm \frac{S_{ess,rq}}{S_{ess,ab}} \times S_{ess,ab,i} \times \frac{1}{\sqrt{1+(\frac{P_{ess,rq}}{Q_{ess,rq}})^2}}$$

  end

else if *(*$P_{ess,c,rq} > 0$ *&* $Q_{ess,d,rq} > 0$*) or (*$P_{ess,d,rq} > 0$ *&* $Q_{ess,c,rq} > 0$*)* **then**

 Charge all the units capable of charging only.

 Discharge all the units capable of discharging only.

 Update the required power as

$$S_{ess,rq} = \sqrt{(P_{ess,c/d,rq})^2 + (Q_{ess,c/d,rq})^2}$$

 for *1:N_{ess}* **do**

  if *The units are capable of bidirectional operation* **then**

$$P_{ess,rq,i} = \pm \frac{S_{ess,rq}}{S_{ess,cd,ab}} \times S_{ess,ab,i} \times \frac{1}{\sqrt{1+(\frac{Q_{ess,rq}}{P_{ess,rq}})^2}}$$

$$Q_{ess,rq,i} = \mp \frac{S_{ess,rq}}{S_{ess,cd,ab}} \times S_{ess,ab,i} \times \frac{1}{\sqrt{1+(\frac{P_{ess,rq}}{Q_{ess,rq}})^2}}$$

  end

end

$$Q_{nres,rq,i} = \frac{S_{nres,rq}}{S_{nres,ab}} \times S_{nres,ab,i} \times \frac{1}{\sqrt{1+(\frac{P_{nres,rq}}{Q_{nres,rq}})^2}} \tag{18}$$

F. LOAD CONTROLLER (LC)

LC takes the required active ($P_{l,rq,i}$) and reactive ($Q_{l,rq,i}$) power from each load center and provides the cumulative active ($P_{l,rq}$) and reactive ($Q_{l,rq}$) power demand to the MGC. The active ($P_{ls,rq}$) and reactive ($Q_{ls,rq}$) power load shedding requirement provided by the MGC is distributed to respective MCs uniformly in proportion to their load requirements according to Eq. 19 and Eq. 20 (see Algorithm 6).

$$P_{ls,rq,i} = \frac{P_{ls,rq}}{P_{l,rq}} \times P_{l,rq,i} \tag{19}$$

$$Q_{ls,rq,i} = \frac{Q_{ls,rq}}{Q_{l,rq}} \times Q_{l,rq,i} \tag{20}$$

Algorithm 5: Proposed Algorithm for NRESC

if *only active or reactive power is required* **then**

 for *1:N_{nres}* **do**

  Turn on the unit at the rated power.

  Update the required power.

  If the required power is met, turn off other units.

  If the required power is negative, operate the current unit at reduced power and turn off other units.

 end

else if *both active and reactive powers are required* **then**

$$S_{nres,rq} = \sqrt{(P_{nres,rq})^2 + (Q_{nres,rq})^2}$$

 for *1:N_{nres}* **do**

$$P_{nres,rq,i} = \frac{S_{nres,rq}}{S_{nres,ab}} \times S_{nres,ab,i} \times \frac{1}{\sqrt{1+(\frac{Q_{nres,rq}}{P_{nres,rq}})^2}}$$

$$Q_{nres,rq,i} = \frac{S_{nres,rq}}{S_{nres,ab}} \times S_{nres,ab,i} \times \frac{1}{\sqrt{1+(\frac{P_{nres,rq}}{Q_{nres,rq}})^2}}$$

 end

end

Eq. 20 is valid for both leading and lagging reactive powers. This is useful if there is some reactive power available at load centres e.g. due to capacitive charging currents in an under loaded line, the reactive power demand in other areas can be fulfilled if the MGC gives a negative reactive power load shedding. In this way, the load centers can be used as balancing areas for reactive powers.

Algorithm 6: Proposed Algorithm for LC

if $P_{ls,rq} > 0$ **then**

$$P_{ls,rq,i} = \frac{P_{ls,rq}}{P_{l,rq}} \times P_{l,rq,i}$$

end

if $Q_{ls,rq} > 0$ *or* $Q_{ls,rq} < 0$ **then**

$$Q_{ls,rq,i} = \frac{Q_{ls,rq}}{Q_{l,rq}} \times Q_{l,rq,i}$$

end

The control algorithms discussed above provide online active and reactive power dispatch functions for grid connected and islanded modes of operation of MGs. These are the steady state modes of operation according to IEEE 2030.7 standard for specification of MG controllers [37]. This makes these algorithms comprehensive as far as the operation of MGs is concerned. Since the control considers generalized parameters like active and reactive power for DESs and SoC for ESUs (batteries, flywheel, etc.), it is applicable to different DESs and ESSs. Moreover, the control algorithms are capable of taking the owner specified limitations for a MS. This capability can be used to operate a MS in different ways. For example, if the user specifies the SoC limits to 0.45 and 0.55, a bidirectional power reserve is maintained for that ESU as in [22]. Same goes for electric vehicles. Here, MSs and MGs are considered to be connected to the grid at POI, so, the control is independent of different types (AC, DC, hybrid, etc.) of MGs and structures (radial, ring, meshed, etc.) of the
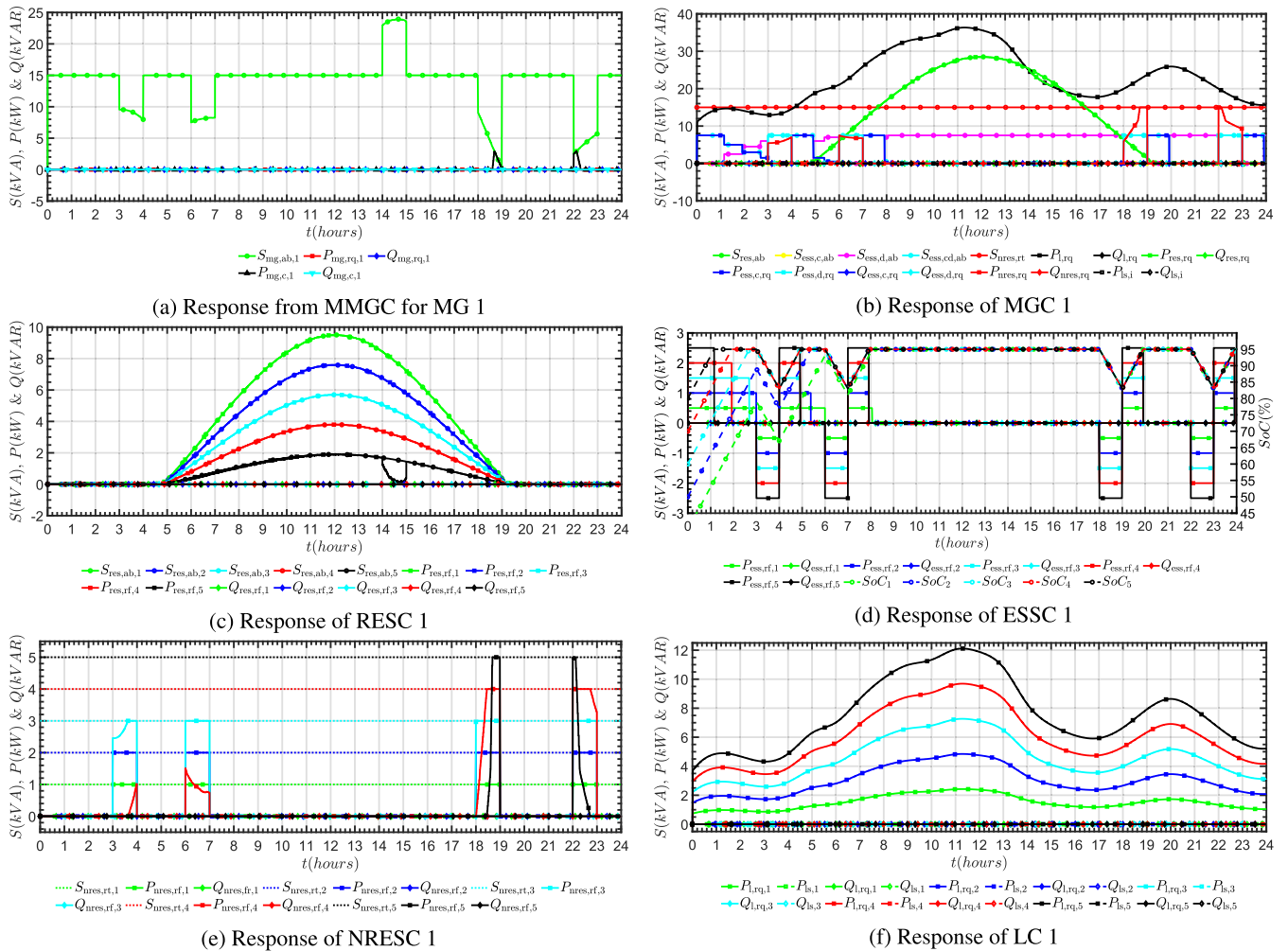
(a) Response from MMGC for MG 1

(b) Response of MGC 1

(c) Response of RESC 1

(d) Response of ESSC 1

(e) Response of NRESC 1

(f) Response of LC 1

FIGURE 2. Responses of MG 1 controllers. MG 1 is operating at unity power factor, so, no reactive power dispatch is performed here. In grid connected mode, RESs operate at MPPT while ESUs are charged. In islanded mode, the load is preferably supplied from RESs. If RESs are not enough to supply the load, ESUs and NRESs are operated in order according to the load demand. Otherwise, excess energy from RESs is curtailed. UCs issue dispatch commands to MCs to meet the requirements of the MGCs.

power network. This makes these algorithms generic with respect to the participants (microsources/microgrids) and network structure. The control algorithms are not dependent on the number of MSs, so, such a control scheme is applicable when the number of MSs and/or MGs increases or decreases. This makes these algorithms modular with respect to the number of MSs and MGs. Only the available/required power is exchanged vertically from UCs to MMGC. The only information exchanged about the nature of a MS is its dispatch related limitations like SoC and rated powers and this information is exchanged only with respective UC. This makes the information exchange minimum thus providing maximum privacy, minimum communication requirements and minimum threat of cyber attacks.

III. RESULTS AND DISCUSSION

Test simulations have been developed for five MGs connected to the main grid. Equivalent models of DESs have been used which can follow active and reactive powers being dispatched

from their MCs. A case study has been developed for a typical day with islandinig instants from 3 to 4, 6 to 7, 14 to 15, 18 to 19 and 22 to 23 hours. Fig. 2 to Fig. 6 show the behavior of MMGC, MGC, RESC, ESSC, NRESC and LC of the respective MG. Solar profiles of the first four MGs are the same whereas the fifth MG has a higher solar profile than others. The first, fourth and fifth MGs are operated at unity power factor while the second and third MGs operate at lagging and leading power factors respectively. The ESUs and NRESs of all the MGs are kept identical with same initial conditions in order to make it easier to understand the behavior of different controllers under different conditions. The responses of different controllers under these conditions are discussed below.

A. RESPONSE OF MMGC
Fig. 2a to Fig. 6a depict the behavior of MMGC for such a MMG structure. Here, a positive coordinated power to a MG

(a) Response from MMGC for MG 2

(b) Response of MGC 2

(c) Response of RESC 2

(d) Response of ESSC 2
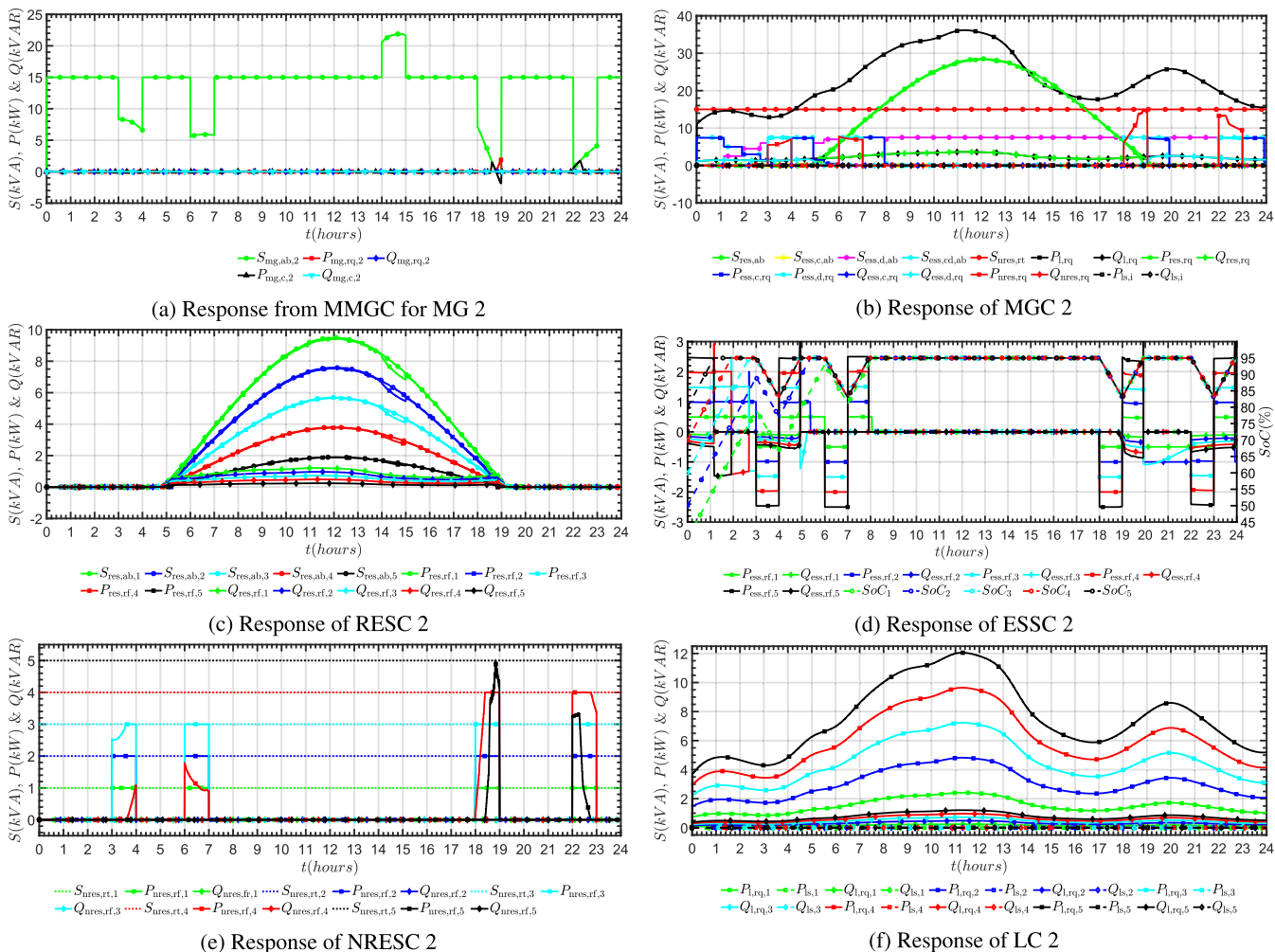
(e) Response of NRESC 2

(f) Response of LC 2

FIGURE 3. Responses of MG 2 controllers. MG 2 operates at a lagging power factor, therefore, reactive power is required. The reactive power demand from the load is sent to MGC through LC which controls the other UCs to operate their respective MCs to meet the load demand.

means that the particular MG is required to produce more equal to its coordinated power to be fed to POI so that it can be used by a needful MG having a negative coordinated power. For example, MG 4 requires active power during 3 to 4 and 6 to 7 hours and this is provided by MG 5 being the geographically nearby MG. During 18 to 19 and 22 to 23 hours, power required by MG 2 and MG 4 are contributed by other MGs according to their geographical location and power provision capacity.

B. RESPONSE OF MG 1 CONTROLLERS

Fig. 2 represents a MG operating at unity power factor. The MGC (Fig. 2b) takes the available and required powers from each unit controller and issues the dispatch commands accordingly. MGC knows the solar power available from all the RESs through RESC. Since no ESU is below its lower SoC limit, $S_{ess,co,ab}$ is zero. The units with SoC greater than the upper limit contribute to $S_{ess,do,ab}$ while the rest of the units contribute to $S_{ess,cd,ab}$. In this way, the MGC knows three available distinct ranges of ESUs to be dispatched

accordingly. The total available power from NRESs is also communicated to the MGC. It is the sum of the rated power of all the NRESs which is constant unless a unit is plugged in or out. Total load demand is also available through LC. So, MGC has powers available from RESC, ESSC and NRESs and power required from LC. Having the available and required powers and the mode of operation (grid connected or islanded), it decides the dispatch commands for the UCs. MGC extracts all the RESs power in grid connected mode to feed the load and the remaining, if any, is fed to grid. In islanded mode, maximum power is extracted to feed the load first and charge the ESUs as a second priority. The leftover power, if any, is curtailed. Same trend can be observed here. In this case, load is operated at unity power factor, so, no reactive power is there from any participant. As far as the ESUs are concerned, they are charged in grid connected mode according to their charging powers and SoC limits. They are charged in islanded mode if the RES power is more than the load demand. Otherwise, they are discharged according to their limits. In this case, load is higher than
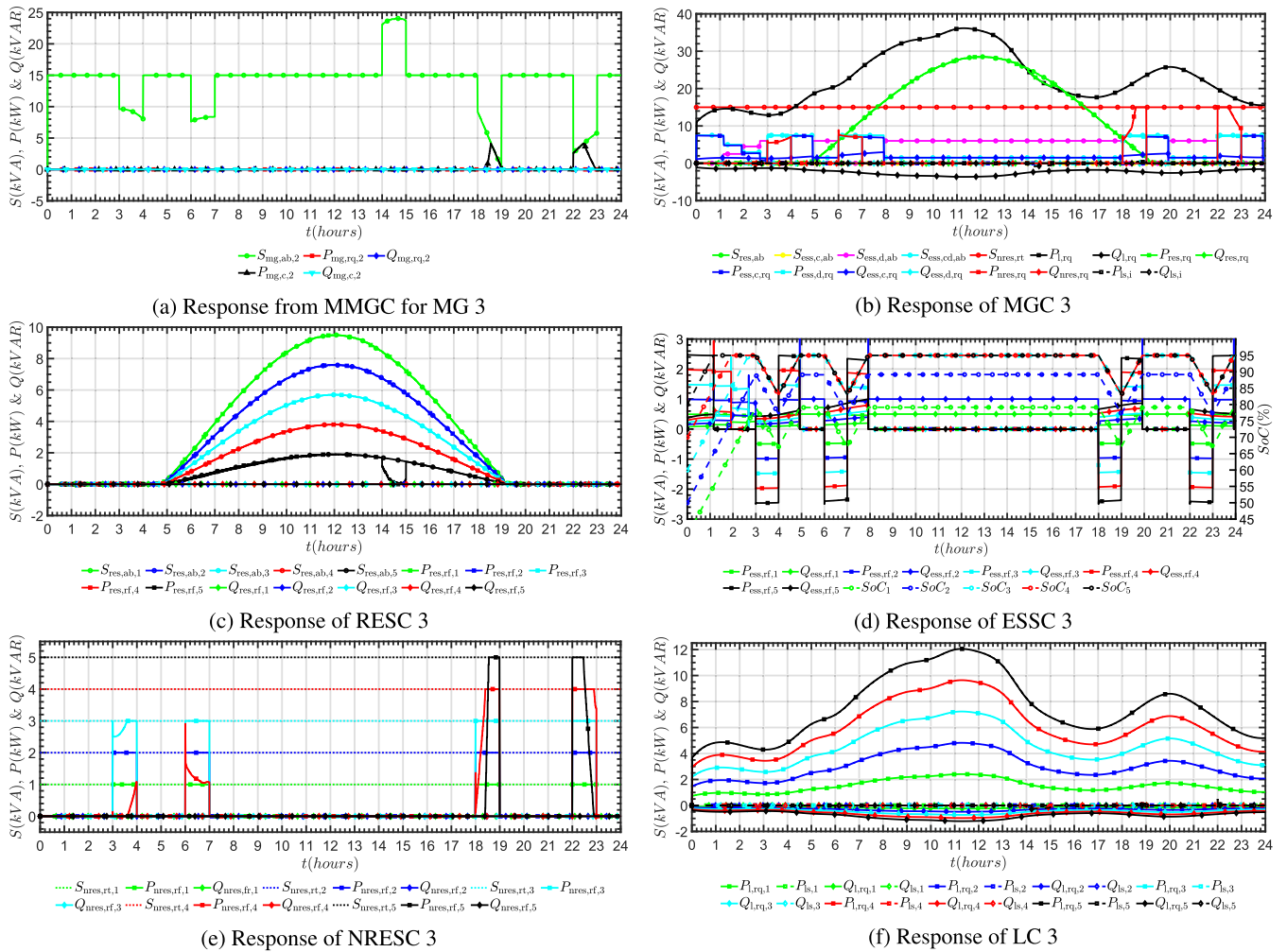
(a) Response from MMGC for MG 3

(b) Response of MGC 3

(c) Response of RESC 3

(d) Response of ESSC 3

(e) Response of NRESC 3

(f) Response of LC 3

FIGURE 4. Responses of MG 3 controllers. MG 3 operates at a leading power factor. This is sensed by MGC and ESUs are used in charging modes accordingly.

$S_{res,ab}$ during islanding period, so, the ESUs are discharged. While they are charged as much as possible during grid tie mode. NRESs are operated only to provide the load in islanded mode if RESs and ESUs are not enough to supply the load. They remain idle in grid connected mode. Same happens here. Since all the resources are enough to fulfill the load, no load shedding requirement is dispatched to the load controller. Fig. 2c shows the response of the RESC of MG 1 after receiving the dispatch commands from the respective MGC. Since the MGC commands the RESC to operate all the RESs at the MPPT, RESC issues dispatch commands to the MSCs accordingly. Only exception is the period of 14 to 15 hours, where the MG is islanded and power from RESs is more than the load, so, curtailment occurs accordingly. Fig. 2d shows the response of the ESSC of MG 1. The ESSC receives the charging and discharging commands from MGC and dispatches the units accordingly. It can be seen that all the chargeable units are charged at their rated powers in grid connected mode in such a way that the $P_{ess,c,rq}$ from the respective MGC is fulfilled. Similarly the units are discharged

or charged in islanded mode to fulfill charging or discharging power requirement from the MGC. NRESs are operated only in islanded mode (Fig. 2e) according to their owner specified order to meet the load demand. They remain idle in grid connected mode as grid is there to provide the power deficit from the load. LC receives the load shedding requirements from the MGC and dispatches the load shedding requirement to each load center. In our case (Fig. 2f), LC remains idle as there is no load shedding required.

C. RESPONSE OF MG 2 CONTROLLERS
Fig. 3 represents a MG operating at a lagging power factor. When there is reactive power demand, the MG tries to compensate it by itself from RESs, ESUs and NRESs. Here, MG issues the reactive power dispatch commands to RESC and ESSC. Since, RESs and ESUs are enough to meet the reactive power demand, NRESs are not used for this purpose. RESC (Fig. 3c) extracts the available power from RESs in the form of active and reactive power to be supplied to the load according to the algorithm. It can be obseverd that MGC
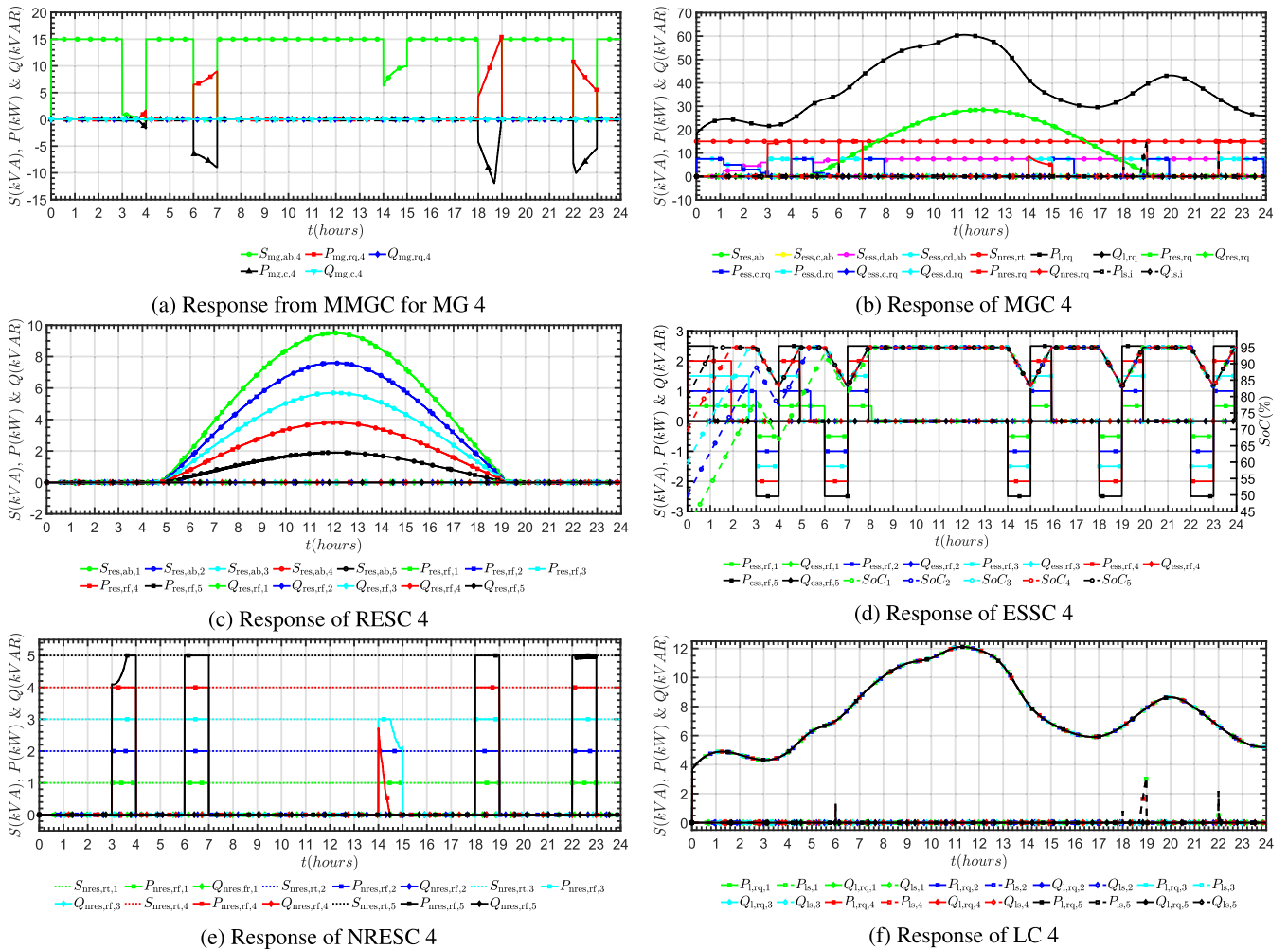
(a) Response from MMGC for MG 4

(b) Response of MGC 4

(c) Response of RESC 4

(d) Response of ESSC 4

(e) Response of NRESC 4

(f) Response of LC 4

FIGURE 5. Responses of MG 4 controllers. MG 4 is heavily loaded and depicts the phenomena of power imports from other MGs when local resources are not enough to meet the load requirements.

issues the requirement to the RESC to utilize the maximum available energy and the RESC dispatches the RESs to meet the demands from the MGC. In this way the lower level RESC and immediate upper level MGC communicate with each other to achieve maximum possible RES penetration. The ESSC (Fig. 3d) charges the ESUs in grid connected mode if the SoC is less than the upper limit and there is no reactive power demand. During islanded mode, ESUs are operated as the solar power is not enough to cope with the load demands. NRESs are operated only in islanded mode (Fig. 3e) if required. Since there is no load shedding required, LC (Fig. 3f) remains idle.

D. RESPONSE OF MG 3 CONTROLLERS

Fig. 4 shows the response of controllers for a MG operating at a leading power factor. MGC performs in a similar manner as discussed before with some differences as far as the reactive power scheduling is concerned. Since the reactive power is leading, MGC controller tries to compensate it by using the $S_{ess,c,ab}$ of the MG. The ESUs are charged and discharged in

grid connected and islanded mode acoording to load demands and SoC constraints as discussed before. So, the ESUs are dispatched with a reactive power charging command in order to compensate the load demand. RESs are dispatched to extract the maximum power available since the load is always greater than the $S_{ess,ab}$ in islanded mode. NRESs come into play in islanded mode when RESs and ESUs are not enough to supply the load demand. Since there is no load shedding, LC does not issue any load shedding dispatch command.

E. RESPONSE OF MG 4 CONTROLLERS

Fig. 5 shows the response of a MG that is identical to the MG 1 except the load in MG 4 is five times the maximum load of MG 1. This represents the condition of a heavily loaded MG. During the grid tie modes, RESs operate at MPPT, ESUs are charged at their rated powers while the NRESs remain idle. This is similar to the response of controllers in MG 1. Any discrepancy in load suply is handled by the grid. During islanded modes, RESs, ESUs and NRESs operate in order to supply the load. This is sufficient during 14 to 15 hours but
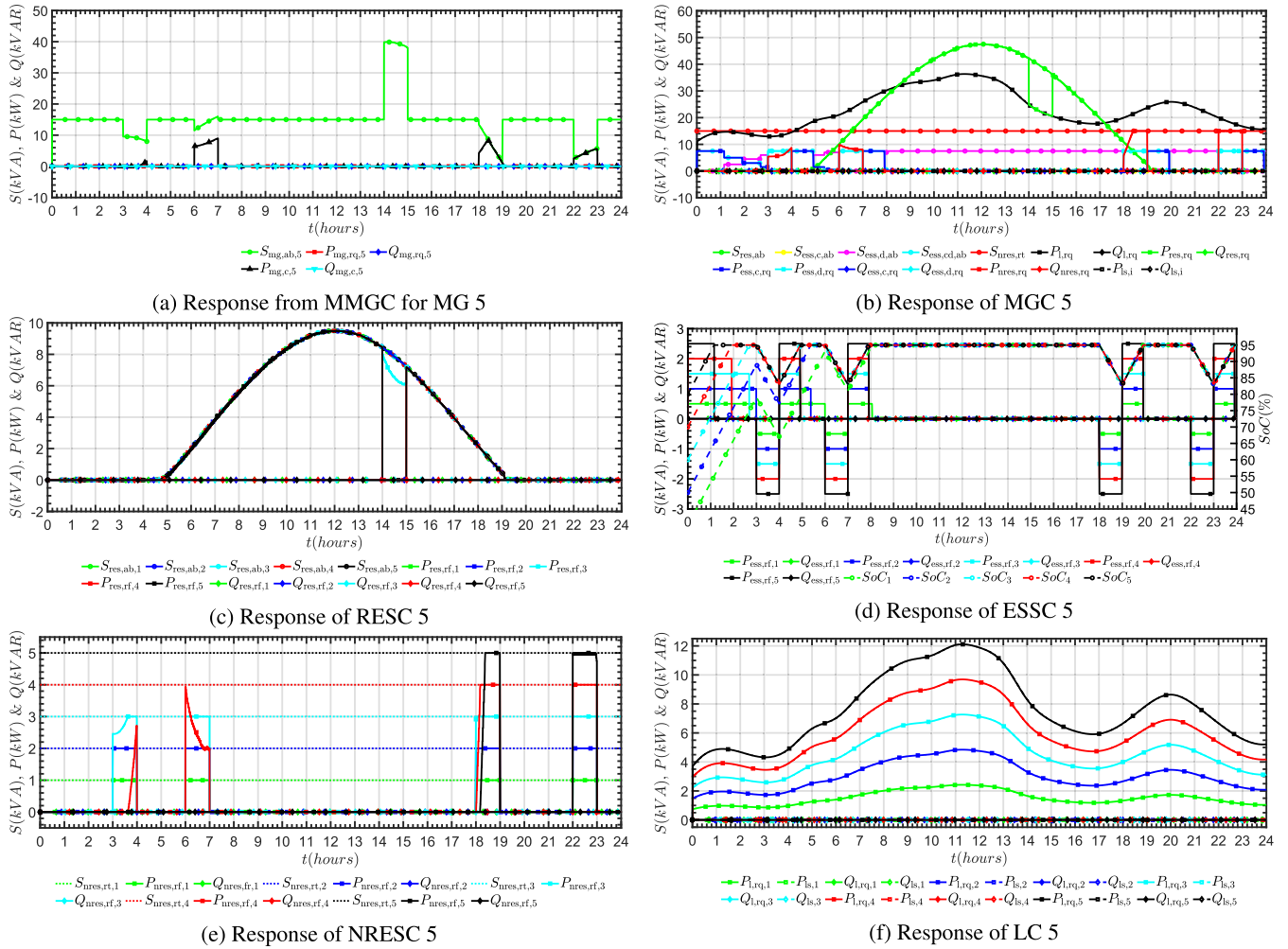
(a) Response from MMGC for MG 5

(b) Response of MGC 5

(c) Response of RESC 5

(d) Response of ESSC 5

(e) Response of NRESC 5

(f) Response of LC 5

FIGURE 6. Responses of MG 5 controllers. MG 5 is lightly loaded and depicts the phenomena of power exports to other MGs in hours of need.

the MG fails to supply the load by its local resources during other islanded instants. In such cases, MMGC comes into play by asking the geographically nearby MGs to contribute if possible. For example, MG 5 provides power during 3 to 4 hours as it is the geographically nearby MG capable of supporting other MGs. Since MG 5 is enough to cope with this power discrepancy, no other MG is involved in this inter-MG power management process. Other MGs can also contribute to make up the power demands of MG 4 if needed as it happens during 18 to 19 and 22 to 23 hours.

F. RESPONSE OF MG 5 CONTROLLERS

Fig. 6 shows the response of a MG that is identical to the MG 1 except the available solar power is five times the available solar power of MG 1. This represents the condition of a lightly loaded MG. The MG controllers respond in a way similar to the controllers of MG 1 in grid tie mode i.e. RESs are operated at MPPT, ESUs are charged at their rated powers, NREESs are kept idle while the load is balanced by the grid. Islanded modes are more interesting. The local resources of

the MG are more than enough to supply the load. So, no load shedding is observed. These extra resources are utilized by MMGC to supply the loads in other MGs during islanding instants where needed. For example, MG 5 supplies MG 4 during 3 to 4 and 6 to 7 hours. During 14 to 15 hours, all the other MGs are self sufficient, so, we see curtailment of RESs in MG 5.

IV. CONCLUSION

This paper proposes a decomposition based hierarchical heuristic control of multimigrogrids. The control strategy decomposes the control problem at four levels of hierarchy namely microsource level, unit level, microgrid level and multimicrogrid level. Microsource controller is for each distributed energy source. A unit controller controls microsource controllers of a particular type in a microgrid. A microgrid controller controls all the unit controllers in a microgrid and all the microgrid controllers are controlled by a multi-microgrid controller. Each microsource controller provides the information of available and required power along with

its dispatch capability to its respective unit controller. Unit controller then determines the overall available and required power of its microsources and conveys this information to its microgrid controller. Microgrid controller then determines the available and required power of its microgrid and conveys this information to the multimicrogrid controller. The multimicrogrid controller determines the dispatch powers of each microgrid based on the available and required power of each microgrid and conveys to each microgrid controller. Each microgrid controller then dispatches its unit controllers to fulfill the dispatch commands from the multimicrogrid controller. Each unit controller then issues the dispatch commands to its microsource to meet the demand from the microgrid controller. Such a decomposition based hierarchical control structure combines the advantages of coordination and effectiveness of centralized control and low communication and computational requirements of the distributed control. A heuristic or rule based approach is adopted as it suits well with the control structure as it is less communication and computational intensive, verifiable by human operators leading to high acceptance and less certification issues. Such a control strategy is capable of providing comprehensive online dispatch functions for active and reactive power flow control for the steady state modes of operation (grid connected and islanded) in compliance with IEEE 2030.7 to maximize the penetration of renewable energy sources and load satisfaction while keeping in view the restrictions of the participants (microsources and/or microgrids). It is generalized to be adopted with respect to different types of participants and grid structure. It is modular with respect to the number of its participants. It also protects the privacy of its participants to maximum possible extent by limiting the information exchange. Simulations are carried out to verify the proposed control scheme.

In future, the proposed control can invoke more sophisticated cost based optimization techniques to improve the performance. Moreover, load management based on continuous and discrete loads can be designed.

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MUHAMMAD ANIQUE ASLAM received the B.Sc. degree (Hons.) in electrical engineering with specialization in power systems from the University of Engineering and Technology (UET), Lahore, Pakistan, and the M.Sc. degree (Hons.) in power engineering from the Technical University of Munich, Germany. He is currently pursuing the Ph.D. degree in electrical engineering with specialization in control of microgrids with UET. He is also working as a Lecturer with the Department of Electrical Engineering, UET. His current research interest includes control of microgrids for high penetration of distributed energy sources.

SYED ABDUL RAHMAN KASHIF received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the University of Engineering and Technology (UET), Lahore, Pakistan. He worked as a Researcher with the Power Electronics Laboratory, University of Paderborn, Germany, from 2009 to 2010. He is currently serving as an Associate Professor with the Department of Electrical Engineering, UET. His research interests include power electronics, control of electrical machines, smart grids, renewable energy systems, and the optimization of power systems.

GHULAM ABBAS (Senior Member, IEEE) received the B.E. degree from the University of Engineering and Technology, Lahore, Pakistan, in 2004, and the M.E. and Ph.D. degrees from the Institute National des Sciences Appliquées de Lyon (INSA Lyon), France, in 2008 and 2012, respectively, all in electrical engineering. He is currently working as an Associate Professor at the Department of Electrical Engineering, The University of Lahore, Lahore. He has published a number of papers in various international and national IEEE conferences and journals of repute, such as IEEE, Elsevier, and MDPI. His research interests include analog and digital controller designs for power switching converters, soft computing, and power system optimization. He is a Reviewer of several premier conferences and journals, including the IEEE Transactions on Industrial Informatics, *Asian Journal of Control*, *Engineering Optimization*, and IEEE Access. He has served as a guest editor for several electrical and computer engineering journals.

NASIM ULLAH (Member, IEEE) received the Ph.D. degree in mechatronics engineering from Beihang University, Beijing, China, in 2013. From September 2006 to September 2010, he was a Senior Design Engineer with IICS, Pakistan. He is currently working as a Full Professor of electrical engineering with Taif University, Saudi Arabia. His research interests include renewable energy, flight control systems, integer and fractional order modeling of dynamic systems, integer/fractional-order adaptive robust control methods, fuzzy/NN, hydraulic and electrical servos, and epidemic and vaccination control strategies.

LUKAS PROKOP graduated the Ing. degree majoring in electrical power engineering from FEEC Brno. He was an Associate Professor at FEI TU Ostrava. Currently, he is engaged in renewable energy sources, modern technologies, and methods in electrical power engineering and electrical measurements. He is a Research Team member of Czech and international research projects. He serves as the Deputy Head of the ENET Research Centre.

VOJTECH BLAZEK was born in Czech Republic, in 1991. He received the Ing. degree from the Department of Electrical Engineering, VSB—Technical University of Ostrava, in 2016, where he is currently pursuing the Internal Doctoral degree. He is also a Junior Researcher at the Research Centre ENET–Energy Units for Utilization of Non-Traditional Energy Sources. His current interest includes developing modern and green technologies in off-grid systems with vehicle to home technologies.

STANISLAV MISAK was born in Czech Republic, in 1978. He received the Ing. and Ph.D. degrees from the Department of Electrical Engineering, VSB—Technical University of Ostrava, in 2003 and 2007, respectively. He is currently a Professor at the VSB—Technical University of Ostrava and the CEO of the Research Centre ENET and Centre for Energy and Environmental Technologies. He holds a patent for a fault detector for medium-voltage power lines. His current research interests include the implementation of smart grid technologies using prediction models and bio-inspired methods.

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