A Multilayer Optimization Scheme to Retain the Voltage and Frequency in Standalone Microgrids

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Abstract—A new technique is proposed in this paper to manage the frequency and voltage of standalone remote area microgrids within predefined limits. To this end, a multilayer approach is used to determine the most suitable actions. The proposed technique contemplates the dynamic supply adequacy and sustainability of the microgrid in addition to the operational costs. It takes action instantly after an event that violates the microgrid’s voltage and/or frequency and adjusts the generation levels of the dispatchable sources and determining the best configuration for the microgrid’s network. It then proceeds to determine the level of power support from available neighboring microgrids and controlling the loads, as well as the charge or discharge power of existing battery storage systems, in addition to curtailing the renewable sources in successive actions. The developed operation-stage technique uses a metaheuristic optimization. The performance of the developed technique is validated through extensive numerical analyses in MATLAB.

Index Terms—Microgrid, Renewable energy, Optimization, Secondary control.

I. INTRODUCTION

Supplying electricity to rural areas has always been a challenge to local utilities as the extension of the network to remote areas is not always economically feasible [1]. To address this problem, a promising tactic is installing and operating distributed generators (DGs) at the vicinity of loads, also referred to as remote area standalone microgrids (MGs). An MG is a cluster of loads supplied locally by renewable energy-driven, converter-interfaced DGs and/or battery energy storage systems (BESs), as well as some conventional synchronous generator type DGs [2-4]. The uncontrolled/non-dispatchable DGs (NDDGs) provide the maximum available power or rated power while controllable/dispatchable DGs (DDGs) are responsible for the voltage and/or frequency (VF) of the MG [5]. The DDGs can share the total load of the MG using several techniques such as the droop control, which is a part of the primary controller for DDGs.

Not only the proper sharing of active and reactive power amongst DDGs is crucial for the stability of the MG, but it can also reduce the overall operational cost of the MG and maintain the VF within the acceptable limits [6]. As an example, [7] proposes a probabilistic approach to optimally select the droop coefficients of DDGs while [8] proposes a method to combine the secondary controller of the MG with the primary controller of DDGs to solve the optimal power sharing problem by only focusing on minimizing the fuel cost and voltage variation. Another scheme is proposed in [9] which has also considered the power loss of the MG. Alternatively, control of BESs, demand response (DR) load-shedding (LS) and renewable curtailment (RC) has been separately used in [10-13] to resolve the VF violation problems in an MG. Alternatively, reconfiguration of the MG network is considered as a cost-effective technique in [14-15] while the possibility of eliminating the VF problem through an external entity (EE) such as a neighboring MG has been proposed in [16-19]. Many studies have focused on the optimal design of MGs at their planning stage while limited works such as [8-9] have focused on their short-term operational stage. A short-term operational planning is important in accommodating the rapid and unexpected variations in the power of loads and renewable-based DGs. Ref. [8-9] have assessed the possibility of adjusting the droop coefficients of DDGs without considering the impact of controlling BESs, DR, LS, RC or network reconfiguration. Also, in addition to cost of fuel of DDGs, power loss and voltage variation, focused in [8-9], many other technical, operational and sustainability criteria are important in defining the optimal operating conditions for an MG such as the MG’s dynamic supply adequacy, spinning reserve, reliability and sustainability which can be a part of decision-making. This is the main research gap that is addressed in this paper.

II. THE DEVELOPED TECHNIQUE

Consider an MG consisting of DDGs and NDDGs, BESs and loads. The DR program is considered at load points to enable shedding non-essential loads or adding future loads. These components are connected through lines among which some are configurable. The MG’s network can be reconfigured with these switchable lines and by turning them on or off. The MG is also connected to EEs to exchange power with. The DDGs are assumed to be droop controlled while the NDDGs inject the maximum possible power to the MG while their output power can be curtailed. The VF at the output of DDGs is calculated from droop equations of [20]
where \( P \) and \( Q \) are respectively the active and reactive power injected by the DG, \( f \) and \( V \) are frequency and voltage magnitude, and \( V_{\text{max}} \) and \( f_{\text{max}} \) are two set-points of the droop lines while \( m \) and \( n \) are the droop coefficients, calculated from

\[
\begin{align*}
\Delta f^\text{max} &= \frac{m^{\text{DDG}} p^{\text{DDG}}}{P_{\text{max}}} \\
\Delta V^\text{max} &= \frac{n^{\text{DDG}} Q^{\text{DDG}}}{Q_{\text{max}}}
\end{align*}
\]

where \( \Delta f^\text{max} \) and \( \Delta V^\text{max} \) are the maximum allowed deviations in the MG’s frequency and voltage magnitude.

The MG is desired to operate with a VF in the range of \( V_{\text{nom}} \pm V_1 \) and \( f_{\text{nom}} \pm f_1 \) (i.e., the safe zone). As far as the VF stay within this zone, the developed VF management technique (VFMT) runs discretely in intervals of \( \Delta T \) (e.g., 10-minute). When the VF exceeds the safe limits, the proposed VFMT acts instantly to bring VF to the desirable safe zone. Fig. 1 illustrates schematically the flowchart of the developed technique.

The developed technique is an operation-stage algorithm as it collects the real values of consumed power by the loads, and then analyzes the current state of the DGs and transmits the optimal operating settings to the local controllers to react. The reaction time of the total process to resolve the VF problem must be smaller than the predefined operation time of the protective relays that operate following VF violation.

The proposed technique is based on a multilayer scheme in which successive layers of actions are carried out. As illustrated schematically in Fig. 2, these layers are:

- layer-1: Droop parameters (i.e., droop coefficients of \( m^{\text{DDG}} \) and \( f^{\text{DDG}} \)) and VF set-points of \( V_{\text{max}} \) and \( f_{\text{max}} \) and switches of the MG’s configurable lines (\( \text{sw}^{\text{CL}} \)),
- layer-2: Power import from or export to available EEs (\( P_{\text{ex}} \)),
- layer-3: Power charge/discharge level of BESs (\( P^{\text{BES}} \)), and
- layer-4: Adjusting RC and DR level (\( \Delta p^{\text{RC}} \) and \( \Delta p^{\text{DR}} \)).

The technique first tries to yield the most optimal condition with minimal cost (i.e., layer-1). If a layer fails to resolve the VF problem, the following layer is considered consequently as the cost rises from layer-1 to 4. This guarantees that the technique removes the VF problem first by low-cost actions (i.e., those of layer-1) before choosing expensive options (i.e., those of layer-2 to 4). To this end, an objective function (OF) has been formed in the form of

\[
OF = \omega_1 OF_{\text{tech}} + \omega_2 OF_{\text{op}} + \omega_3 OF_{\text{sus}} + \omega_4 OF_{\text{adq}}
\]

where \( OF_{\text{tech}}, OF_{\text{op}}, OF_{\text{sus}} \) and \( OF_{\text{adq}} \) are respectively the technical, operational, dynamic adequacy, and sustainability assessment costs while \( \omega_1, \omega_2, \omega_3, \omega_4 \) are their corresponding weightings (importance) i.e., \( \sum_1^4 \omega_i = 1 \). Fig. 3 illustrates each of these OFs and their breakdowns.

Eq. (3) is minimized considering the constraints of

\[
\begin{align*}
\Delta f &< \Delta f_{\text{max}} \\
|\Delta V| &< |\Delta V|_{\text{max}} \\
l_i &< l_i^{\text{max}}
\end{align*}
\]

among which (4a) and (4b) show the maximum allowed deviation of frequency in the MG (\( \Delta f \)) and deviation of voltage magnitude (\( |\Delta V| \)) at all of its buses; (4c) represents the thermal limits of its lines while (4d) shows the loading limits of DDGs whereas (4e-f) denote the minimum downtime/uptime and the maximum ramp up/down rate of DDGs. In (4b), \( \alpha_{\text{DDG}} \) is the percentage of minimum loading of a DDG based on its efficiency constraints.

A. Technical OF (\( OF_{\text{tech}} \))

\( OF_{\text{tech}} \) minimizes the deviations of VF from their nominal values, and is derived as

\[
OF_{\text{tech}} = \max(|\Delta V|) + |\Delta f| + \text{Penalty}
\]
where
\[
\text{Penalty} = \begin{cases} 
10^6 & \exists |\Delta V_i| > \Delta V^{\text{max}} \text{ or } |\Delta f| > \Delta f^{\text{max}} \\
0 & \text{otherwise}
\end{cases}
\]
where \(\Delta V_i\) denotes the voltage deviation in bus-\(i\). The value of \(\text{Penalty}\) is set very high to eliminate those sets of variables that cause unacceptable VF deviations.

**B. Operational OF** (\(OF_{op}\))

\(OF_{op}\) represents the operational cost of the MG, and is defined as
\[
OF_{op} = \alpha_1 C_{gen} + \alpha_2 C_{BES} + \alpha_3 C_{ex} + \alpha_4 C_{sw} + \alpha_5 C_{loss} + \alpha_6 C_{CC}
\]
(6)
where \(C_{gen}, C_{BES}, C_{ex}, C_{sw}, C_{loss},\) and \(C_{CC}\) are respectively the power generation cost by DGs, the life loss cost of BESs, the energy trading cost with EEs, the cost of switching configurable lines, the cost of power losses in lines, and the cost of sacrificing customer comfort by controlling their loads under DR, while \(\alpha_1\) to \(\alpha_6\) are empirical coefficients equalizing the impact of these costs.

\(C_{gen}\) is calculated as
\[
C_{gen} = \sum_i \left( P_{DG}^{\text{fuel}} C_{fuel}^i + C_{O&M}^i + C_{life}^i \right) \Delta T
\]
(7)
where \(P_{DG}^{\text{fuel}}\) is the output power of the DGs over the \(\Delta T\) period, \(C_{fuel}\) and \(C_{O&M}\) are respectively the fuel consumption of the DG (in liter/kWh) and its corresponding cost (in $/liter), \(C_{O&M}\) is the operation and maintenance cost (in $/hr), and \(C_{life}\) represents the life loss cost of the DG, which is defined as
\[
C_{life} = \frac{C_{cap}^{DG}}{T_{op}}
\]
(8)
where \(T_{op}\) and \(C_{cap}^{DG}\) are respectively the total operation lifetime in hours and the capital cost of DG.

\(C_{BES}\) is defined as \([21-22]\)
\[
C_{BES} = \sum_i \left( P_{BES}^{\text{SoC}} \right) \frac{\Delta T}{E_{life}^i} C_{BES}^i
\]
(9)
in which the charge/discharge power of the BES (in kW), its total cumulative throughput in its life cycle (in kWh), and its capital cost (in $/kWh) are respectively denoted by \(P_{BES}^{\text{SoC}}, E_{life}^i\), and \(C_{BES}^i\) while \(\lambda^{\text{SoC}}\) is a coefficient, provided in \([21]\), to consider the impact of the SoC.

\(C_{ex}\) is formulated as
\[
C_{ex} = \left( \sum_i \left( P_{ex}^{imp} \right) (C_{cost}^{ex})^{imp} - \sum_j \left( P_{ex}^{exp} \right) (C_{cost}^{exp})^{exp} \right) \Delta T
\]
(10)
where \(C_{cost}^{ex}\) is the power exchange costs (in $/kWh) while \(^{imp}\) and \(^{exp}\) represent the import and export of power respectively. 

\(C_{sw}\) is derived from
\[
C_{sw} = N_{sw} \text{ Cost}_{sw}
\]
(11)
where \(N_{sw}\) and \(\text{Cost}_{sw}\) are respectively the total number of switchings to connect or disconnect a configurable line, and its corresponding cost (in $/switching).

\(C_{loss}\) is calculated from
\[
C_{loss} = P_{loss} \text{ Cost}_{loss} \Delta T
\]
(12)
in which \(P_{loss}\) is the power loss (in kW), and \(\text{Cost}_{loss}\) is its associated cost (in $/kWh).

\(C_{CC}\) is formulated as
\[
C_{CC} = \sum_i \left( \Delta P_{DR}^{\text{shed}} \right) \text{ Cost}_{DR}^{\text{shed}} + \sum_i \left( \Delta P_{DR}^{\text{future}} \right) \text{ Cost}_{DR}^{\text{future}}
\]
(13)
in which \(\Delta P_{DR}\) is the amount of load modified under the DR (in kW) in which \(\text{shed}\) and \(\text{future}\) respectively denote those nonessential loads that have been shed or the additional future-planned load turned on under the DR while \(\text{Cost}_{DR}\) represents the corresponding costs (in $/kWh).

**C. Sustainability OF** (\(OF_{sus}\))

\(OF_{sus}\) considers the cost associated with RC, emissions from DGs, contribution of renewable energy in the MG and MG’s dependency on EEs, while
\[
OF_{sus} = \beta_1 C_{RC} + \beta_2 C_{Em} + \beta_3 C_{RCI} + \beta_4 C_{EDI}
\]
(14)
in which \(C_{RC}, C_{Em}, C_{RCI}\), and \(C_{EDI}\) are respectively the cost of curtailing NDDGs, the emission cost of DGs, the cost corresponding to the ratio of non-renewable-based DGs over the total generation, and the cost of MG’s dependency on EEs, while \(\beta_1\) to \(\beta_4\) are empirical coefficients for equalization. \(C_{RC}\) is calculated as
\[
C_{RC} = \sum_i \Delta P_{RC}^{\text{shed}} \text{ Cost}_{RC}^{\text{shed}} \Delta T
\]
(15)
where \(\Delta P_{RC}^{\text{shed}}\) and \(\text{Cost}_{RC}^{\text{shed}}\) are respectively the amount of RC (in kW) and its associated cost (in $/kW). \(C_{Em}\) is defined as
\[
C_{Em} = \sum_i \left( P_{DG}^{Em} \right) \text{ Cost}_{Em} \Delta T
\]
(16)
where \(\text{Cost}_{Em}\) are respectively the emissions of DGs for electricity generation (in Tonne/kWh) and its corresponding cost (in $/Tonne). \(C_{RCI}\) is formulated as
\[
C_{RCI} = \text{ Cost}_{RCI} \left( 1 - RCI \right)
\]
(17)
in which \(RCI\) is an index which represents the contribution of renewable-based DGs, and is defined as
\[
RCI = \sum_i \left( P_{DG}^i / \sum_k P_{DG}^k \right)
\]
(18)
and \(\text{Cost}_{RCI}\) is its corresponding per unit cost (in $). \(C_{EDI}\) is presented as
\[
C_{EDI} = \text{ Cost}_{EDI} \times EDI
\]
(19)
where \(EDI\) is an index representing the MG’s dependency on the EEs, and is derived as
\[
EDI = \sum_i |S_{i}^{ex}| \sum_j S_{j}^{load}
\]
(20)
where $S_{\text{ex}}$ and $S_{\text{load}}$ are respectively the apparent power that the MG exchanges with EEs and consumed by the MG’s loads while $C_{\text{ED1}}$ is its corresponding per unit cost (in $\text{s}$).

**D. Dynamic Adequacy OF ($OF_{\text{adq}}$)**

$OF_{\text{adq}}$ considers the dynamic supply adequacy of the MG, and reflects the probability of energy not supplied (ENS) within the MG and the MG’s spinning reserve (SR). It is formulated as

$$OF_{\text{adq}} = \gamma_1 C_{\text{ENS}} + \gamma_2 C_{\text{SR}}$$

where $C_{\text{ENS}}$ and $C_{\text{SR}}$ are respectively the cost of ENS and low SR while $\gamma_1$ and $\gamma_2$ are empirical coefficients for equalization. $C_{\text{ENS}}$ is presented as

$$C_{\text{ENS}} = \text{Cost}^{\text{ENS}} ENS$$

where $ENS$ is derived from the given availability ($Av$) of DGs, BESs and EEs as [23]

$$ENS = \sum (1 - Av_i) |P_i| \Delta T$$

(in kW) and Cost$^{\text{ENS}}$ is its corresponding cost (in $\text{s/kWh}$). $C_{\text{SR}}$ is expressed as

$$C_{\text{SR}} = \frac{\text{Cost}^{\text{SR}}}{SR}$$

in which SR represents the readily available SR within the MG, defined by

$$SR = \sum (P_{i}^{\text{DDG}})_{\text{max}} - P_{i}^{\text{DDG}}$$

while Cost$^{\text{SR}}$ is its corresponding cost (in $\text{s/kWh}$).

To solve the $OF$ of (3), an MPSO-based optimization approach is used in this paper with a particle, in the form of Fig. 4. The MPSO’s process includes initialization, finding individual best particle and global best particle, and updating the velocity and particles until convergence, as discussed in [24].

**IV. PERFORMANCE EVALUATION**

To assess the performance of the proposed VFMT, several study cases are analyzed for an MG under consideration in MATLAB; a few of which discussed below. Consider the MG of Fig. 5 with 3 DDGs, 2 NDDGs, 2 BESs, 2 configurable lines (i.e., line-1 and 2) and one connection to a neighboring MG as the available EE. DDG-1 and DDG-2 are assumed respectively as biomass and diesel-driven synchronous generators while DDG-3 is solar-driven, VSC-based DG (with a power smoothing storage that makes it dispatchable). Thereby, DDG-1 and DDG-3 are assumed to be renewable-based DDGs. NDDG-1 and 2 are thought as small-scale VSC-based wind turbines operating under maximum power tracking scheme and thus, are non-dispatchable. The safe zone of VF are supposed as $1 \pm 0.05 \text{ pu}$ and $50 \pm 0.5 \text{ Hz}$ while $V_{\text{max}} = 1.1 \text{ pu}$, $V_{\text{min}} = 0.9 \text{ pu}$, $f_{\text{max}} = 51 \text{ Hz}$, $f_{\text{min}} = 49 \text{ Hz}$.

The MG lines are assumed to have impedances as those of [25]. Table I lists the considered technical parameters in modeling this MG for the numerical analyses while Table II provides all considered costs, weightings and coefficients in the numerical analyses.
costs, coefficients, and weightings.

A. Case-1

Assume an event in which the active power demand of the MG increases suddenly and as a result, the MG’s frequency drops to 49.35 Hz. To resolve the frequency violation, the VFMT reacts immediately and brings the frequency to 50 Hz by adjusting the dispatch of the DDGs and importing a small amount of power from the EE. The contribution of each component of the MG, the voltage magnitudes at all buses and MG’s frequency before and after applying the VFMT are presented in Fig. 6a.

B. Case-2

Consider an event in which the voltage magnitude at bus-1, 2 and 4 get below 0.95 pu as a result of the sudden increase in reactive power consumption within the MG, while the frequency is within its safe zone as shown in Fig. 6b. Hence, the VFMT takes action and imports power from the EE to supply 7% of the demand. The contribution of the solar-based DDG increases by 5% while the contribution of the rotating DDGs reduces by 12%, which improves the MG’s sustainability and operational aspects.

C. Case-3

Assume an event in which the frequency increases to 50.55 Hz and beyond the safe zone as the active power consumption within the MG drops unexpectedly and the output power of the NDDGs increase abruptly. Thus, the VFMT initiates and decides to export 0.03 pu power to the EE (i.e., 8% of the total power generated by all DGs of the MG) while a small amount of NDDGs output power is curtailed to bring down the MG’s frequency (see Fig. 6c).

D. Case-4

Assume an event in which the voltages at bus 9 and 10 of the MG respectively increase to 1.059 and 1.062 pu and beyond the safe zone as the reactive power demand of the MG reduces unpredictably. Thereby, the VFMT reacts and brings the voltages into the safe zone by altering the power dispatches from the DDGs by reducing the output power of DDG-2 and 3 while increasing the output power of DDG-1 as shown in Fig. 6d. Hence, the total contribution of DDGs does not change, and no other modifications are applied.

E. Case-5

Consider an event in which the voltage magnitude of most of the MG buses are beyond the safe zone, and MG’s frequency drops to 49 Hz as the active power demand of the MG sharply increases. As a result, the VFMT decides to change the droop set-points of DDGs ($V_{\text{max}}^\text{OF}$ and $f_{\text{max}}^\text{OF}$) from 1.05 pu and 51 Hz to 1.08 pu and 51.5 Hz along with optimally setting the droop coefficients as well as switches off (de-energizing) line-1 and imports 0.023 pu power from the EE as shown in Fig. 6e. On top of that to resolve the VF violation, the VFMT also discharges BESs by 0.03 pu power while a small amount (i.e., 0.01 pu) of loads are shed under the DR.

F. Case-6

Consider an event in which a load demand of 0.66 pu is shared equally by the DDGs while the VF of MG are within the safe zone.
Assuming after $\Delta T$ time (see Fig. 1), the VFMT analyzes and further improves the MG’s operation by transferring 5% of its load from the diesel-based DDG-2 to the biomass-based DDG-1 as shown in Fig. 6f. As a result, the costs of $OF_{sus}$ and $OF_{op}$ reduces respectively by 15 and 20% though the cost of $OF_{adq}$ increases by about 15% from the initial event. Nevertheless, both the overall $OF$ and power loss in the MG reduce by 8%. Hence, the VFMT improves the system performance even when the VF is within the safe zone.

V. CONCLUSION

This paper has presented a new technique to manage the VF of standalone MGs within the desired predefined safe zones using a multilayer approach. An optimization-based technique is utilized to this end, which considers technical, operational, dynamic supply adequacy and sustainability of the microgrid when selecting the suitable decision variables. The conducted numerical analyses validate that the technique first adjusts the droop parameters for the DDGs and reconfigures the MG network as these are the cheapest options. However, if the technical constraints are not satisfied, it proceeds to determine external power support from an available neighboring microgrid followed by controlling the charge or discharge power of existing BESs and loads, as well as curtailing the renewable sources.

REFERENCE