Power Loss and Total Load Demand Coverage in Stand-Alone Microgrids: A Combined and Conventional Droop Control Perspectives

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ABSTRACT Conventional droop control plays an essential role in microgrids with distributed generators, DGs, and variable load demand. Despite its advantages, the conventional droop scheme does not take into account the minimization of power losses and the maximization of the total load coverage. Moreover, most of the nonconventional droop control studies that address power loss consider one variable load. This study proposes a combined droop scheme and inspects its effects on power loss minimization and total load coverage. The proposed scheme combines conventional and nonconventional droop schemes and constructs a 3D $P-f$ droop characteristic that takes into account the presence of two variable loads. Four and six-bus microgrids are adopted to simulate and illustrate the system behavior in MatLab. Results are compared to the standard fully conventional droop approach; results showed that the combined scheme has higher performance in terms of power loss gain and total load coverage.

INDEX TERMS Combined droop control, distributed generators, microgrids, power losses minimization, total load coverage.

I. INTRODUCTION

Nowadays, electrical energy is one of the fundamentals without which life is unimaginable. With the continuous growth in population and prosperity worldwide, the electric power demand continuously increases. This led to several crucial challenges in power availability, losses, and power system stability and reliability. Distributed generation and microgrid (MG) systems were proposed and used as plausible solutions to these challenges, [1]. This means, the local generation and sharing of electric power to cover the MG’s variable load demands at their local sites. Literature inspection showed that the conventional droop control is one of the most used schemes to achieve this objective, [2]. It employs a power-sharing scheme among several distributed generators (DGs) to cover the MG’s local load demands.

One of the main advantages of MGs with local DGs is the minimization of the main distribution line losses and the employment of renewable energy sources. Despite this and because of the limited power capacity of the DGs, especially the renewable energy ones, power loss minimization continues to be one of the most important challenges in microgrid systems. Moreover, the use of multiple DGs created new voltage and frequency matching challenges. This made the development of new MGs control schemes an essential requirement for efficient MGs operation. The new schemes have to ensure efficient power-sharing among distributed generators and enhancement of power losses while preserving frequency and voltage matching.

Microgrid control is based on a three-level hierarchical architecture; the primary level is responsible for power-sharing and voltage and frequency regulation. The secondary level deals with frequency/voltage restoration and real-time resynchronization and compensation. While the tertiary deals with optimal energy management and power flow...
control. Droop control is one of the control schemes of the primary level; it is employed to adjust the MG frequency and voltage and to set the power contribution of each inverter in both on-grid and standalone modes [3].

Literature inspection showed that there are conventional and nonconventional droop control schemes. Conventional droop control uses fixed droop coefficients, i.e., static droop lines, to define the generator characteristics in the active power-frequency (P-f) and reactive power-voltage (Q-V) planes. The conventional droop controller equations, of the kth generator, are defined by (1) and (2), [4]. These characteristics aim to control the contribution of each of the DGs in covering the load demand and preserving the permissible frequency and voltage limits.

\[
\omega = \omega_0 - m_p P_G \\
|V_k| = |V_0| - n_Q Q_G
\]

where:

- \( P_G, Q_G \): active and reactive powers of the DG.
- \( m_p \): the P-f droop line coefficient.
- \( n_Q \): the Q-V droop line coefficient.
- \( \omega_0 \): no load frequency.
- \( |V_0| \): no load voltage.

Nonconventional droop control aims to overcome the disadvantages of the static droop lines of the conventional scheme. In nonconventional droop control, the P-f and Q-V characteristics are changed to take into account the power losses and other power-sharing related factors such as load changes and DGs capacities. Literature review showed that a few nonconventional droop schemes have tackled the issue of power losses in MGs, [5], [6], [7], [8], [9], [10]. Hence, the role of nonconventional droop control in MGs power losses needs further inspection.

A thorough survey concerning MG installation, power flow control, protection system, and the role of smart grids and their weaknesses and future possibilities have been presented in [2]. A non-conventional control technique that estimates reactive power-sharing errors through little real power interruptions to improve power control and sharing accuracy has been proposed in [11]. The proposed technique was applied to both grid-connected and stand-alone microgrids. An effective method to achieve accurate power-sharing even when the communication between DGs is interrupted was proposed and compared with the results of conventional droop in [12]. A method to determine the best DG locations for droop-based microgrids while considering the secondary control to obtain minimum power losses was proposed in [13]. It considered three strategies a P-\(f\)/Q-V droop, a P-\(V\)/Q-f droop, and a master/slave scheme.

A review of primary control techniques for voltage and frequency regulation and inverters’ stability in MG with linear loads was developed in [14]. A new control strategy to enhance microgrid operation and reliability was introduced in [15]; the study included modeling, stability analysis, and control of parallel MG inverters. An improved scheme with a reactive power-sharing and parallel inverters circulating-current limiting was proposed in [16]. The study employed an optimization technique to determine the best droop parameters that reduce voltage and frequency deviation in islanded MGs.

Power flow (PF) is another important issue in MGs, especially in islanded mode. MG’s do not have an explicit slack bus, thus power flow algorithms should cope with this issue. The study in [17] selected the highest capacity DG bus as a slack bus and considered the other busses as PV or PQ busses. The work in [18] adopted a power-flow algorithm in which several DG busses cover the role of the slack bus. A modified Gauss-Seidel (GS) method for PF analysis in islanded MGs with droop control was developed in [19]. Bus voltages were calculated using conventional Gauss-Seidel, whereas system frequency was controlled using droop schemes. Despite the simplicity of GS, the Newton-Raphson (NR) method is more frequently used, especially in high-dimension power systems, because of its faster convergence.

The Newton-Raphson method was employed in [20] to solve the PF problem in islanded MGs. The problem formulation took into account the frequency deviation and the slack bus absence, [21]. It solved the power flow problem in a hybrid MG using a modified Newton-Raphson method. The effect of introducing a virtual impedance in the droop model in islanded MG power flow analysis was tackled in [22]. Sufficient conditions for the convergence of the NR method for both master-slave and droop controllers were presented in [23].

Optimal PF (OPF) methods in islanded MGs were discussed and compared in [24]. An OPF method based on imperialist-competitive with genetic algorithms was employed in [25]. The proposed method was also compared with a genetic algorithm, Newton-trust, and time-domain methods. Particle swarm optimization was employed in [26] to improve power-sharing during load variation. It used a voltage-characteristic compensation scheme to deal with the load increments. A globally convergent Newton-trust region method was presented, in [27]; it formulated the islanded-MG PF problem as a set of nonlinear equations. A backward/forward sweep method was employed in [28] to solve the PF problem in radial microgrids. Here, one of the droop busses was chosen as a global voltage reference. A heuristic approach based on glow-worm swarm optimization to minimize power losses was used in [29]. A fast-decoupled load-flow algorithm in islanded MGs with droop control was proposed in [30].

A particle swarm optimization for real-time self-tuning of the power control parameters was presented in [31]. The control scheme considered load-changing conditions, harmonic distortion, and frequency and voltage regulation. Four droop control techniques were examined and compared in [32]. The study employed nonlinear loading in the plug-and-play operation of an islanded MG. The impact of using a nonconventional droop model on power-sharing, voltage regulation, system efficiency, and stability was tackled in [33].
The effects of adopting a nonconventional droop approach to achieve voltage regulation and improve reactive power-sharing accuracy were also discussed in [34]. A metaheuristic OPF algorithm was also used to analyze power flow in electric distribution networks [35]. It combined a particle swarm algorithm, a genetic algorithm, and the black hole method to solve the OPF problem. The work in [36] classifies the optimal power flow methods under different conventional and renewable energy sources constraints.

Although various researchers considered MGs with high bus numbers (9, 34, . . .), the literature review showed that they usually assumed and adopted droop schemes with single load variations. Hence, the issues of simultaneous variations in two loads at different busses, the effect of the load change location with respect to the nonconventional droop controller, and the total load coverage with nonconventional droop schemes were not sufficiently tackled. In this study, a combined droop control scheme is proposed. The combined scheme employs optimization in the P-f plane to reduce and minimize the MG power losses with two variable loads. Four and six–bus islanded MGs are used to inspect the performance of the combined scheme and compare their responses with the fully conventional droop method. The main contributions of this study are:

- Formulation of the microgrid OPF problem in the P-f plane and its solution under frequency, voltage, and DGs’ maximum capacities constraints.
- Construction of the 3D P-f characteristic of the combined scheme that achieves the minimum power losses with two variable loads and a relatively high R/X ratio.
- Determination of the effect of the combined scheme on the total load coverage with different R/X ratios cables.
- Determination of the effect of the location of the nonconventional controller of the combined scheme on power losses and total load coverage.
- Comparison of the combined and fully conventional droop methods.

The rest of the paper is organized as follows: section II introduces the OPF problem formulation including the 4-bus and 6-bus MGs structures, loads and lines models, the DGs characteristics, and the MG-adopted Newton-Raphson algorithm. Section III illustrates the nonconventional droop characteristic construction algorithm and its OPF pseudocode, and the simulation settings. Sections IV and V present the 3D nonconventional droop characteristics, the operation scenarios, and the results of the combined and fully conventional droop schemes applied to the 4-bus and 6-bus MGs, respectively. Section VI presents the conclusions of the paper.

II. PROBLEM FORMULATION

The study aims to use a nonconventional droop approach to enhance the MG performance with respect to the conventional droop scheme. The proposed combined scheme sets the DGs best power-sharing points that minimize power losses and maximize the total shared load coverage. The set point has to achieve the frequency and voltage matching conditions and maintain their values within the permissible limits. The study tackles the steady-state operation of the microgrid, and the problem is formulated as follows:

Consider the following active and reactive power loss equations (3), [21]:

\[
\begin{align*}
P_{\text{loss}} &= \frac{1}{2} \sum_{k=1}^{N} \sum_{m=1}^{N} \Re \{ Y_{kn} (V_k^* V_m + V_m^* V_k) \} \\
Q_{\text{loss}} &= -\frac{1}{2} \sum_{k=1}^{N} \sum_{m=1}^{N} \Im \{ Y_{kn} (V_k^* V_m + V_m^* V_k) \}
\end{align*}
\]

Determine:

\[
\min_{P_{\text{loss}}} \min L_d m_{p_{\text{dc}}}
\]

Subjected to (4):

\[
\begin{align*}
P_{\text{DG}k_{\text{min}}} &\leq P_{\text{DG}k} \leq P_{\text{DG}k_{\text{max}}} \\
Q_{\text{DG}k_{\text{min}}} &\leq Q_{\text{DG}k} \leq Q_{\text{DG}k_{\text{max}}} \\
\omega_{\text{min}} &\leq \omega_k = \omega \leq \omega_{\text{max}} \\
|V_{k_{\text{min}}}| &\leq |V| \leq |V_{k_{\text{max}}}| \\
\text{the } k^{\text{th}} \text{ line current} : |I_k| &< |I_{k_{\text{max}}}| \\
\text{the } k^{\text{th}} \text{ conventional droop lines slopes} : \\
m_{pk} &\text{ is constant} \\
n_{qk} &\text{ is constant} \\
\text{the } k^{\text{th}} \text{ nonconventional droop slopes} : \\
n_{q_{pk}} &\text{ is constant} \\
P - f \text{ droop } - \text{ slopes search range} : \\
m_{p\text{min}} &\leq m_{p_{\text{dc}}} \leq m_{p\text{max}}
\end{align*}
\]

With \( L_d \), \( m_{p} \), and \( m_{p_{\text{dc}}} \) the load demand, the \( P-f \) droop coefficients vectors, and the coefficient of the \( k^{\text{th}} \) nonconventional \( P-f \) droop line slope. The \( n_{q} \) and \( n_{q_{pk}} \) variables are the \( Q-V \) droop coefficients vectors and the \( Q-V \) coefficient of the \( k^{\text{th}} \) nonconventional droop line slope, respectively. \( N \) is the number of busses and \( |I_{k_{\text{max}}}| \) the \( k^{\text{th}} \) line maximum current that satisfies the voltage constraints.

\( P_{\text{DG}} = [P_{\text{DG}1} P_{\text{DG}2} \ldots P_{\text{DG}N}], Q_{\text{G}} = [Q_{\text{DG}1} Q_{\text{DG}2} \ldots Q_{\text{DG}N}], P_{\text{Ld}} = [P_{\text{Ld}1} P_{\text{Ld}2} \ldots P_{\text{Ld}N}], \) and \( Q_{\text{Ld}} = [Q_{\text{Ld}1} Q_{\text{Ld}2} \ldots Q_{\text{Ld}N}] \) are the DGs and loads active and reactive power vectors, respectively. \( P_{\text{loss}} \) and \( Q_{\text{loss}} \) are the
distribution lines’ active and reactive power losses, and \( V = [V_1, V_2, \ldots, V_N] \) is the busses’ voltage vector with the \( k \)th bus voltage magnitude \(|V_k|\) and phase-angle \( \delta_k \).

The combined scheme can employ a single nonconventional controller and a set of conventional ones or a set of nonconventional and conventional controllers. In both cases, the conventional controllers’ droop line slopes, and the \( Q-V \) slopes of the nonconventional controllers of the combined scheme, are fixed and computed by (1) and (2). On the other hand, the values of the \( m_{p, nc} \) coefficients of the nonconventional controllers vary in an interval, Fig. 2. Hence, in the first case, adopted in this study, the \( m_{p, nc} \) variable adds a one-dimensional constraint to the optimization domain and in the second multiple constraints are added to the optimization problem domain. Accordingly, the best values of each \( m_{p, nc} \) component are determined by the optimization algorithm and correspond to the optimal solution.

The problem formulation assumes the following:

1) LOAD MODEL

The load is assumed to depend on the frequency, it is adopted from the model presented in [37], (5) and (6), for the load case \( \alpha = \beta = 0, K_{pf} = 1, \) and \( K_{gf} = -1 \).

\[
P_{Ld,k} = P_{0Ld} \left( \frac{|V_k|}{|V_r|} \right)^\alpha \left( 1 + K_{pf} (\omega - \omega_0) \right) \tag{5}
\]

\[
Q_{Ld,k} = Q_{0Ld} \left( \frac{|V_k|}{|V_r|} \right)^\beta \left( 1 + K_{gf} (\omega - \omega_0) \right) \tag{6}
\]

where \( \omega_0 \) and \( \omega_r = 100\pi \) are the operating and nominal frequencies, respectively. \(|V_r|\) is the nominal voltage and \( P_{0Ld} \) and \( Q_{0Ld} \) are the nominal active and reactive powers. \( K_{pf} \) and \( K_{gf} \) are the frequency sensitivity coefficients, [37].

2) LINE MODEL

The line model assumes the line impedance to change with the operating point frequency. The line impedance, connecting the \( k \)th and \( n \)th busses, is defined by (7).

\[
Z_{kn}(\omega) = R_{kn} + jX_{kn}(\omega) \tag{7}
\]

The bus admittance matrix, \( Y_R(\omega) \), of an \( N \)-bus microgrid is defined in (8). With the admittance values defined by (9), [21].

\[
Y_R(\omega) = \begin{bmatrix} Y_{11}(\omega) & \cdots & Y_{1N}(\omega) \\ \vdots & \ddots & \vdots \\ Y_{N1}(\omega) & \cdots & Y_{NN}(\omega) \end{bmatrix} \tag{8}
\]

\[
Y_{kn}(\omega) = \sum_{k=1}^{N} Z^{-1}_{kn}(\omega) \quad \forall k \neq n \tag{9}
\]

3) DG MODEL

In this study, all the DG busses will be considered droop busses because the minimization of \( P_{loss} \) is based on the best DGs’ power-sharing rates in total load coverage. In this mode the DGs’ active and reactive powers are controlled according to the droop characteristics, [21].

4) MICROGRID MODEL

The four-bus (4-bus) MG of Fig. 1(a), adopted from [7] but employed with two variable loads, and the six-bus (6-bus) MG of Fig. 1 (b) are used to show the performance of the combined scheme and compare it to the standard fully conventional one.

![FIGURE 1. Structure of the MGs used in the simulation and inspection of the performance of the combined and fully conventional schemes. (a): 4-bus MG, (b): 6-bus MG.](image)

The 4-bus system, Fig. 1 (a), is composed of two variable load busses (B2 and B3) and two droop DG busses (B1 and B4). The 6-bus MG, Fig. 1 (b), is composed of two variable loads at B3 and B6, two fixed loads at B2 (0.1 pu) and B5 (0.2 pu), and three droop DG busses (B1, B2, and B3).

The distribution lines are assumed to be 500m-50mm² and (200-300) m-50mm² Aluminum cables with R/X = 7.7129, for the 4-bus and 6-bus MGs, respectively. Other cable types, that is, Aluminum 35 and 25mm² with R/X ratios of 10.4554 and 13.8208 are also used to compare the total load coverage capability of the fully conventional droop control and the proposed combined scheme. The DGs characteristics are illustrated in Table 1.

5) MICROGRID POWER-FLOW EQUATIONS

A Modified Newton Rapson, MNR, method, [21], is employed to solve the MG PF problem. The method takes into account the absence of a slack bus, the existence of droop busses, and the frequency-dependent admittances. The microgrid’s variables vector is \( x = [\delta_p, |V_p|, \omega, |V_1|]^T \), with \( \delta_p = [\delta_2, \delta_3, \ldots, \delta_N] \) and \( |V_p| = [|V_2|, |V_3|, \ldots, |V_N|] \), the second to the \( N \)th bus voltages phase-angle and magnitude vectors.
TABLE 1. Characteristics of the 4-bus and 6-bus MG-DGs.

| Generator # | 4-bus MG | 6-bus MG |
|-------------|----------|----------|
|             | DG1 [min max] | DG2 [min max] | DG3 [min max] |
| Active power (P) | [0 0.30] | [0 0.20] | [0 0.50] |
| Reactive power (Q) | [0 0.18] | [0 0.12] | [0 0.3] |
| Conventional m_p | 1*10^4 | 4*10^5 | 6.66*10^5 |
| Conventional n_q | 2.53*10^3 | 1.68*10^3 | 1.01*10^3 |

Values are in per-units with S_base = 100 KVA, V_base = 380 V, and \( \omega_{base} = 314 \text{ rad} \cdot \text{s}^{-1}, f_{max} = 0.98 \text{ pu}, f_{avg} = 1.02 \text{ pu}, V_{max} = 0.96 \text{ pu}, V_{min} = 1.04 \text{ pu}. 

\(|V_1| \) and \( \delta_1 = 0 \) the magnitude and phase-angle of bus 1, which is assumed to be the reference bus.

The MNR formulation is illustrated by the set of equations (10) and the algorithm pseudocode presented in Fig. 5:

\[
\Delta x = J^{-1} \cdot D_{P,Q} \tag{10}
\]

With

\[
D_{P,Q} = \begin{bmatrix} P_S - P_BQ_S - Q_BP_{tot} - P_{sys}Q_{tot} - Q_{sys} \end{bmatrix}^T, \quad P_S = [P_{S2}P_{S3} \ldots P_{SN}] = P_{DG} - P_{Ld} \\
Q_S = [Q_{S2}Q_{S3} \ldots Q_{SN}] = Q_{DG} - Q_{Ld} \\
P_B = [P_{B2}P_{B3} \ldots P_{BN}] \\
Q_B = [Q_{B2}Q_{B3} \ldots Q_{BN}]
\]

considering the following network PF equations, [21]:

\[
P_{Blk}(\Delta \delta_k, \Delta V_k, \omega, V_1) = |V_k| \sum_{n=1}^{N} |V_n| \cos(\delta_k - \delta_n - \theta_{kn}) \\
Q_{Blk}(\Delta \delta_k, \Delta V_k, \omega, V_1) = |V_k| \sum_{n=1}^{N} |V_n| \sin(\delta_k - \delta_n - \theta_{kn}) \\
P_{sys}(\Delta \delta_k, \Delta V_k, \omega, V_1) = \sum_{k=1}^{M} P_{DGk} = \frac{1}{\omega_{max} - \omega} \sum_{k=1}^{M} m_{pk} \\
Q_{sys}(\Delta \delta_k, \Delta V_k, \omega, V_1) = \sum_{k=1}^{M} Q_{DGk} = \frac{1}{\omega_{max} - \omega} \sum_{k=1}^{M} n_{pk} \\
P_{tot} = P_{Ld} + P_{loss} \\
Q_{tot} = Q_{Ld} + Q_{loss} \\
J = Jacobian(P_B, Q_B, P_{sys}, Q_{sys})
\]

III. CONSTRUCTION OF THE NONCONVENTIONAL DROOP CHARACTERISTICS AND SIMULATION SETTINGS

The power losses depend on the values of the loads at the load busses, the capacities of the DGs and their distance from each load, and their contribution to load demand coverage. Hence, the characteristic of the nonconventional droop controller is generated by the optimal solutions of (3) subjected to (4). The search for the DGs’ best power-sharing rates, at a given load demand, is based on the search for the \( P-f \) droop line with the best operating point, \( S_{pi} \), which minimizes the power losses, Fig. 2.

The optimization method is an iterative reconfigure, solve PF, and search and select minimum method. That is, the droop controller, with variable droop-line slope (4), is configured by selecting an initial droop-line \( m_{p,nc} \). The DGs contributions and the other PF parameters that characterize the minimum power loss solution are determined using the MNR algorithm. The droop controller is then reconfigured by selecting a new \( m_{p,nc} \), Fig. 2, and the new PF solution is computed. The new power loss value is compared to the minimum value and its PF solution parameters are updated accordingly. The process is iterated for all the range of \( m_{p,nc} \) values, with proper step size. The final solution defines the optimal point for the selected load configuration.

The construction of the complete nonconventional droop characteristic is obtained by the aggregation of the optimal points at all the permissible load configurations. In each case, the optimal point has to satisfy the frequency, voltage, and DGs constraints.

The two variable loads nonconventional 3D \( P-f \) characteristic construction algorithm pseudocode is shown in Fig. 3, Fig. 4, and Fig. 5. The function main(), Fig. 3, includes all the steps that determine the 3D \( P-f \) construction points, it employs the two pseudocode functions check_result(), Fig.4, which checks that the solution satisfies the MG constraint, and MNR(), Fig. 5, which determines the solution of the PF problem for a given \( m_{p,nc} \) point. The used terms and
main()

initialize x, Ld_pf;
Begin
1: repeat
P_{0,ld}(P_{0,ld,min}; P_{0,ld,step}; P_{0,ld,max})
1.2: repeat
Q_{0,ld,k} = \frac{P_{0,ld,k}}{Ld_pf,k} \cdot \sqrt{1 - \frac{Ld_pf,k}{Ld_pf,k}}
1.3: end
1.2: repeat
m_{pr}(m_{pr,min}; m_{pr,step}; m_{pr,max})
1.2.1: c all MNR; %c all MG MNR
1.2.2: if (P_{loss} \geq P_{loss,min}) then goto 1.2; else
1.2.3: call check constraints;
1.2.3.1: if check_result == 1 then x_{op} =
1.2.3.2: x_{op} = P_{vecr}, \%P_{vecr}, Q_{vecr}, Q_{vecr} = Q_{vecr} end if check_result
1.2.4: end
1.2.5: goto 1.2;
1.3: end % end repeat over m_{pr}
1.4: store (Ld, m_{pr}, x_{op}, P_{vecr}, Q_{vecr})
1.5: goto 1
2: end % repeat over P_{0,ld}
end % end Begin
end % end main

FIGURE 3. Main pseudocode of the 4-bus system two-dimensional P-f characteristic construction algorithm.

function check_constraints()
input: x, P_{vecr}, Q_{vecr}:
output: x, P_{vecr}, Q_{vecr}:
Begin:
1: check_result = 1;
2: if \omega \notin [\omega_{min}, \omega_{max}] then check_result = 0;
2.2: goto return;
3: end % end if \omega
4: repeat
4.1: if P_{ck} \notin [P_{ck,min}, P_{ck,max}] or Q_{ck} \notin [Q_{ck,min}, Q_{ck,max}] or \{W_k\} \notin \{W_k_{min}, W_k_{max}\} or \{\delta_k\} \notin \{\delta_{k-min}, \delta_{k-max}\} then check_result = 0;
4.2: end % end if
5: end % end repeat
6: repeat
6.1: if L_{k, k+1} \geq L_{max} then check_result = 0;
6.2: end % end if
7: end % end repeat
8: return check_result
end % end Begin
end % end function

FIGURE 4. Pseudocode of the check_constraints function that checks the validity of the MNR solution.

their definitions are included in Table 2. The pseudocodes
together implement (3), (4), and (10) for the 4-bus system.

A. SIMULATION SETTINGS
The following sections present 3D P-f nonconventional droop
characteristics of the 4-bus and 6-bus MGs of Fig. 1. More-
over, they show the performance of the combined droop
scheme and compare it to that of the fully conventional

one. The comparison is done in terms of the power-loss
gain, P_{loss_gain}, and total load coverage. The first simulated
scenario uses the nonconventional controller with the higher
capacity DG and the second uses it with the lower capacity
one. Moreover, the total load coverage of the combined and
fully conventional schemes is obtained for different cable R/X
ratios. The simulation and analysis are firstly done using
the 4-bus MG to keep the focus on understanding the effects

function MNR()
input: P_{0,ld}, Q_{0,ld}, x, P_{vecr}, Q_{vecr}, tol_{max};
output: x, P_{vecr}, Q_{vecr};
initialize: \omega, \nu, P_{vecr}, Q_{vecr};
Begin:
1: repeat
tol_{max};
1.1: Y_{bus} = Y_{bus}(\omega);
1.2: repeat
k=1, n
1.2.1: P_{ld,k} = P_{0,ld,k}(1 + K_{pf}(\omega - \omega_p);
1.2.1: Q_{ld,k} = Q_{0,ld,k}(1 + K_{pf}(\omega - \omega_p);
1.3: end
1.4: P_{0} = 0; Q_{0} = 0;
1.5: repeat
k=1, n
1.9: end % end repeat k
1.10: repeat
k=1, M
1.10.1: P_{DGD} = \frac{1}{m_{pr}}(\omega_{max} - \omega); \quad Q_{DGD} = \frac{1}{m_{pr}}(W_{max} - W_k);
1.11: end
1.12: P_{sys} = \sum_{k=1}^M P_{DGD}; \quad Q_{sys} = \sum_{k=1}^M Q_{DGD};
1.13: repeat
k=2, N
1.13.1: P_{SR} = P_{DGD} - P_{ld,k}; \quad Q_{SR} = Q_{DGD} - Q_{ld,k};
1.14: end
1.15: P_{tot} = \sum_{k=1}^W P_{ld,k} + P_{loss}; \quad Q_{tot} = \sum_{k=1}^W Q_{ld,k} + Q_{loss};
1.16: D_{P,Q} = [P_{0} - P_{0}; Q_{0} - Q_{0}; P_{tot} - P_{sys} \quad Q_{tot} - Q_{sys}];
1.17: f = Jacobi(P_{0}, P_{0}, P_{sys}, Q_{sys})
1.18: x = x + f^{-1} \cdot D_{P,Q}
1.19: tol = \frac{\|D_{P,Q}\|}{m};
2: end % end repeat tol
3: return x, P_{vecr}, Q_{vecr};
end % end Begin
end % end function

FIGURE 5. 4-bus system MG MNR pseudocode.
of the combined scheme, avoiding the effects of the MG structure complexities. The analysis of the 6-bus MG is then developed to inspect the validity of the results in a more complex structure.

The simulation uses the pu bases, and DGs characteristics illustrated in the MG model of section II. Concerning the load characteristics, literature studies generally assume MGs with fixed loads on all the busses except on one bus, [7], [38], [39], [40]. The range of variations of the variable load is locally regulated so that the total load is below the maximum capacity of the DGs. With two variable loads, the issue becomes more complicated and the two loads have to be regulated simultaneously to ensure that their total value does not violate the DGs capacity constraints. Accordingly, the two loads followed the model of section II with \( L_{d1,1} = L_{d1,2} = 0.95 \), and \( P_{0,Ld} \) values that vary, with a properly defined step-size, between \( P_{0,Ld,\text{min}} \) and \( P_{0,Ld,\text{max}} \). For maximum load coverage, \( P_{0,Ld,\text{min}} \) was set to zero, and \( P_{0,Ld,\text{max}} \) was set so that the sum of the two loads could be covered by the two DGs in a power-sharing scheme, taking into account \( P_{\text{loss}} \) and the other MG constraints. Thus, in all cases, the domain of variations of the two loads is a subset of the triangular domain of Fig. 6.

IV. COMBINED AND FULLY CONVENTIONAL DROOP SCENARIOS: 4-BUS MG

The 4-bus system analysis and simulation results with two variable loads are presented in the following subsections.

A. THE 3D DROOP CHARACTERISTICS: NONCONVENTIONAL DG1 CONTROLLER

The combined scheme nonconventional and conventional droop controllers were firstly placed at the higher-capacity DG1 and the lower capacity DG2, respectively. The simulation was then repeated with the fully conventional droop scheme, i.e. with DG1 and DG2 controllers’ fixed droop lines.

The \( P-f \) nonconventional characteristic was obtained using the algorithm presented in Fig. 3, Fig. 4, and Fig. 5. Results show that the power loss minimization, the DGs contributions, and the droop characteristic are affected by both \( B_2 \) and \( B_3 \) load values and their total sum, Fig. 7 (a), (c), and (d). Therefore, the use of the 2D droop characteristic of the droop controller becomes insufficient to characterize the nonconventional droop controller. Hence, the 3D \( P-f \) characteristic, Fig. 7 (a), should be used in order to characterize the nonconventional controller response at any permissible combination of the two variable loads. Whereas, the conventional droop controller of the combined scheme and the two droop controllers of the fully conventional scheme continues to operate according to their standard 2D fixed slopes characteristics.

It is important to observe that for a given load at one of the variable load busses, the 3D \( P-f \) characteristic has a set of possible operating points, Fig. 7 (c) and (d). These points depend on the loading of the other variable load bus. Thus determining the nonconventional controller operation frequency adds the requirement of measuring the nonconventional controller proximal load. Despite this, it is important to assert that this requirement does not require the exchange of synchronization information between the droop controllers, which is the basic constraint in the droop control approach. In fact, the 3D characteristic determines the operation frequency of the nonconventional controller at the measured load, and the conventional controller static \( P-f \) droop line determines the same frequency, since their DGs contribution is defined by the OPF solution.

B. POWER LOSSES GAIN: NONCONVENTIONAL CONTROLLER AT DG1

The same simulation settings were also used to compare the power losses in the combined and fully conventional schemes with two variable loads. Result, Fig. 7 (b), shows the existence of a power loss gain in the combined scheme, defined as a percentage \( P_{\text{loss gain}} \% \) (11), with respect to the standard fully conventional scheme.

\[
P_{\text{loss gain}} \% = \frac{P_{\text{loss fullyconv}} - P_{\text{loss combined}}}{P_{\text{loss fullyconv}}} \times 100\% \quad (11)
\]
TABLE 2. The glossary of terms and definitions used in the pseudocode.

| Term | Definition | Term | Definition |
|------|------------|------|------------|
| N    | Number of busses | W    | Number of load busses |
| M    | Number of droop busses | \( L_d = \{L_d_1, L_d_2, \ldots, L_d_N\} \) | The loads |
| \( x = [\delta \ \omega \ \mathcal{V}_1 \mathcal{V}_2]^T \) | Power flow (PF) vector | \( P_c = [P_{c_1}, P_{c_2}, \ldots, P_{c_M}] \) | Droop busses active power |
| \( P_{\text{load}} = [P_{L_1}, P_{L_2}, \ldots, P_{L_M}] \) | Rated-frequency active power | \( Q_c = [Q_{c_1}, Q_{c_2}, \ldots, Q_{c_M}] \) | Droop busses reactive power |
| \( L_{d_{1,2}} \) | Load k power factor | \( V_{d_{1,2}} \) | The loads active power |
| \( \text{variable}_{\text{opt}} \) | Variable optimal value | \( P_{\text{loss}} \) | The loads reactive power |
| \( p_{\text{act}} \) | PF active Power vector | \( t_{o}, t_{o,\text{max}} \) | PF tolerance and max-tolerance |
| \( q_{\text{act}} \) | PF reactive power vector | \( m_{\text{pf}}, m_{\text{pf},k} \) | Droop bus-k \( P_f/Q_f \) coefficients |

The same figure shows that the gain is higher for low loading at the proximal B2 bus (Ld1) and high loading at the distal B3 (Ld2). In fact, Fig. 7 (c) and (d) show that in this case, the OPF solution decreases the contribution of the distal DG1 and increases the contribution of the proximal DG2 generators in covering the high Ld2 value. In this case, Ld1 is mainly covered by its proximal higher capacity generator DG1 (B1). Hence, this power-sharing solution minimizes the losses with respect to the standard fully conventional scheme in which the contribution rates of DG1 and DG2 are fixed. The maximum \( P_{\text{loss gain}} \% \) was 26.265% for Ld1 = 0 and Ld2 = 0.3 pu. The gain drop at higher Ld2 values is due to the fact that DG2 power capacity has been fully exhausted, Fig. 7 (d). Thus, DG1 has to deliver a higher power value to the distal B3 bus in order to cover the Ld2 increment, Fig. 7 (c).

It is also important to observe that the power loss gain is very small (almost zero) for low Ld2 at B3 and high Ld1 at B2. In fact, in this case, the contribution of the DGs is conditioned by the fixed rate of the conventional controller of the combined scheme. That is, the conventional controller of the combined scheme forces DG2 to contribute with its fixed rate in covering the total load. Because of the low proximal load at B3, the rest of the generated power is delivered to the distal load at B2, which leads to higher power losses. Hence, in this case, the performance of the combined scheme is almost equal to the fully conventional scheme.

C. TOTAL LOAD COVERAGE: NONCONVENTIONAL DG1 CONTROLLER

Three different Aluminum cables of 50, 35, and 25 mm² were used to inspect the effect of the combined scheme and the R/X ratio on the total load coverage and compare it to the fully conventional one.

Results, Fig. 8, show that the combined scheme is superior to the fully conventional scheme in terms of total load coverage. The gain in total load coverage of the combined scheme is due to the higher flexibility in the DGs’ power sharing and the power loss gain. Results also show that the gain in total load coverage of the combined schemes, with respect to the standard fully conventional one, becomes higher and more important at higher R/X ratios. This gain can be useful in some MG structural and operation conditions. For example, increasing the DGs capacities (adding PV panels) and loads values, within an MG that uses a 25mm² cable, could require the substitution of the distribution cables with ones of a higher section. However, in certain cases, the use of the combined scheme could be useful to cover the loading increment in the new MG without changing the cables.

It is important to observe, Fig 8 (a), (b), and (c) that the enhancement in the load coverage occurs in the distal load from DG1, i.e., Ld2 and it is higher for lower proximal Ld1 values. This is due to the higher contribution of DG2 and lower contribution of DG1 in high Ld2 coverage, Fig. 7 (c) and (d), as was illustrated in subsection (B). In addition, it is important to emphasize that the reduction in the total load coverage for higher R/X cables, in both the combined and fully conventional cases, is due to the violation of the maximum permissible line-voltage drop constraint.

D. EFFECT OF THE NONCONVENTIONAL DROOP CONTROLLER LOCATION

To study the effect of the location of the nonconventional controller, in terms of the DG capacity with which they operate, the places of the nonconventional and conventional droop controllers of the combined scheme were exchanged. That is, the nonconventional controller was placed at the lower capacity DG2, B3-side, and the conventional one at the higher capacity DG1, B1-side. The 3D P-f characteristic Fig. 9 (a) has now the triangle base on the DG2 side, instead of DG1, because the power-loss minimization process is based on changing the contribution of DG2. Moreover, the width of the base is smaller because of the smaller available manageable power of DG2 with respect to DG1.

The \( P_{\text{loss gain}} \) and DGs power contributions plots of Fig. 9 (b), (c), and (d) show a clear dependence on the location of the nonconventional controller of the combined
scheme. In fact, Fig. 9 (b) shows that despite the existence of a $P_{\text{loss\_gain}}$, it is about 10 times smaller than that in which the nonconventional scheme operated with the higher capacity DG\textsubscript{1}. Moreover, the gain is higher for low loading at the nonconventional controller proximal bus (Ld1) and high loading on the distal one (Ld3) as in the previous case. In this case, the OPF solution reduces the power delivered from DG\textsubscript{2} to the distal Ld\textsubscript{1} and increases the contribution of DG\textsubscript{1} with respect to the fully conventional case, Fig. 9 (c) and (d). Whereas increasing Ld\textsubscript{2}, Fig. 9 (b), requires a higher contribution from the distal higher capacity DG\textsubscript{1} generator, which increases the power losses.

Results also show that with the nonconventional controller of the combined scheme at the lower DG\textsubscript{2} capacity side, there is no enhancement in the total load coverage in all cable cases. In fact, the total load coverage was the same as that obtained by the fully conventional scheme (blue areas in Fig. 8).

### V. COMBINED AND FULLY CONVENTIONAL DROOP SCENARIOS: 6-BUS MG

To verify the validity of the 4-bus MG response to the combined controller, the same simulation scenarios were repeated with the 6-bus MG presented in Fig. 1 (b). The two variable loads were assumed to be at B\textsubscript{4} (Ld\textsubscript{1}) and B\textsubscript{6} (Ld\textsubscript{3}). Moreover, to study the effect of the location of the nonconventional controller of the combined scheme, the capacity DG\textsubscript{1} (B\textsubscript{1}). In each case, the other two controllers operated as conventional droop controllers. Results were also compared to the fully conventional control scheme that operates with three conventional controllers at DG\textsubscript{1}, DG\textsubscript{2}, and DG\textsubscript{3}.

Simulation results showed that the two variable loads 3D P-f characteristics continue to have the triangular form obtained with the 4-bus system. Fig. 10 (a) and (b) shows the DG\textsubscript{1}-DG\textsubscript{3} and DG\textsubscript{2}-DG\textsubscript{3} characteristics for nonconventional DG\textsubscript{3} controller, and Fig. 11 (a) and (b) shows the DG\textsubscript{2}-DG\textsubscript{1} and DG\textsubscript{2}-DG\textsubscript{1} for nonconventional DG\textsubscript{1} controller. The displacement of the head of the triangle from the vertical axis is due to the presence of the additional fixed loads on B\textsubscript{2} and B\textsubscript{3}.

Results of the employment of the combined scheme in the 6-bus MG also showed the presence of a $P_{\text{loss\_gain\%}}$ (11) with respect to the case of fully conventional droop control, Fig 10 (c) and Fig. 11 (c). Results also show similar behavior to the 4-bus case. In fact, Fig. 10 (c) and Fig. 11 (c) show that the $P_{\text{loss\_gain\%}}$ was higher with the nonconventional controller operating at the higher capacity DG\textsubscript{3} side (47.09% versus 4.6% in the other case). Moreover, the same figures show that the $P_{\text{loss\_gain\%}}$ was higher for low loading at the nonconventional controller proximal bus and high loading at the distal bus, as in the 4-bus MG. The contributions of DG\textsubscript{1}, DG\textsubscript{2}, and DG\textsubscript{3} to the total load coverage at every permissible load distribution are also shown in Fig. 10 (d), (e), and (f) and Fig. 11 (d), (e), and (f) with the nonconventional controller operating at DG\textsubscript{3} and DG\textsubscript{1}, respectively.

Regarding the total load coverage in the 6-bus MG, Fig. 12 shows that the results are similar to the 4-bus MG. In fact, the total load coverage of the combined scheme, with the nonconventional droop at the higher capacity DG\textsubscript{3} side, was enhanced with respect to the standard fully conventional scheme. Moreover, the enhancement was higher for the load proximal to the lower capacity DG\textsubscript{1} (Ld\textsubscript{1}) as in the 4-bus case. Despite the lower total load coverage in the lower section cables, due to the line-voltage drop constraints, Fig. 11 (a), (b), and (c) show that the enhancement was higher for lower R/X cables also as in the
gain was higher when the nonconventional controller of the combined scheme operated at the higher capacity DG-side. Therefore, the location of the nonconventional controller of the combined scheme has to be determined based on the MG structure and characteristics. Moreover, results showed that the nonconventional droop controller of the combined scheme should employ 3D \( P-f \) characteristics and not the 2D ones as in the conventional droop controller. This adds the requirement of the knowledge, remote measurement of the nonconventional controller proximal load. Despite this, the droop control basic principle of the absence of communication information between the droop controllers is preserved.

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