2.4. ЭНЕРГЕТИКА И ЭЛЕКТРОТЕХНИКА

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Управление гибридной микросетью с использованием оптимизированного контроллера поддержки сети

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Интеграция различных распределенных источников энергии в энергосистему требует специальной топологии сети и структуры системы управления. Рассматриваемая энергосистема представляет собой гибридную микросеть, состоящую из подсистем постоянного и переменного тока с возможностью управления генерацией и нагрузкой в обеих подсистемах. Для достижения требуемых эксплуатационных характеристик микросети предложено использование частоторегулирующего контроллера с оптимизированными параметрами, обеспечивающего регулирование электрического режима в подсистемах с заданным статизмом. Указанный контроллер подключен к двунаправленному преобразователю, управляющему перераспределением мощности между сторонами переменного и постоянного тока. Кроме того, для выделения подсистемы постоянного тока на изолированную работу реализована соответствующая функция на верхнем уровне системы управления микросетью. Выделение подсистемы постоянного тока на изолированную работу необходимо для предотвращения разряда аккумуляторных батарей и защиты ответственных нагрузок на стороне постоянного тока. Предложенный алгоритм управления микросетью, реализованный в контроллере, позволяет сохранять устойчивость подсистемы переменного тока при совместной работе с подсистемой постоянного тока. Проанализированы режимы работы с выделением подсистемы постоянного тока на изолированную работу и оценена эффективность предложенной системы управления.

Ключевые слова: гибридная микросеть, двунаправленный преобразователь мощности, регулирование режимных параметров и частоты, распределенная генерация.

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Hybrid Microgrid Control Using an Optimized Grid Supporting Controller

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The integration of various distributed energy sources into a power system requires special grid topology and control system structure. The power system considered is a hybrid microgrid comprising DC and AC subsystems with a possibility to control the generation and load in both subsystems. To achieve the required microgrid performance characteristics, it is proposed to use a frequency adjusting controller with optimized parameters, which maintains the electric operation modes in both subsystems with the preset droop. The controller is connected to a bidirectional converter that controls the redistribution of power between the grid AC and DC sides. In addition, for islanding the DC subsystem for isolated operation, an appropriate function has been implemented at the microgrid control system upper level. The islanding of the DC system for isolated operation is necessary to prevent the storage batteries from becoming discharged and to protect the critical loads on the DC side. Owing to the proposed microgrid control algorithm implemented in the controller, stability of the AC subsystem is maintained during its joint operation with the DC subsystem. The operation modes with islanding the DC subsystem for isolated operation have been analyzed, and the effectiveness of the proposed control system has been evaluated.

Key words: hybrid microgrid, bidirectional power converter, control of operating parameters and frequency, distributed generation.

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Introduction

The environmental and economic factors have encouraged a large penetration of distributed generators (DGs). Most of these generators are the renewable type which indicates that the reliance on the high polluting power plants can be reduced. With the sufficient installation of distributed generators, parts of the electricity grid could be operated independently as Microgrids which will result in stabilizing the load profile for power operators and minimizing the negative impacts of utilizing the massive power turbines in regulating electricity grid changes. However, due to the intermittent nature of these generators and the power electronic converters utilized in their integration, the reliability of the power grid and efficiency in regulating disturbances significantly deteriorated. On the other hand, when a proper control system is implemented, an improvement in the efficiency and performance of Microgrids is guaranteed. A Hybrid Microgrid can effectively integrate both AC loads and DC resources and ensure controlled power-sharing [1, 2]. These DC resources are employed to support the network and achieve better control over the AC and DC loads, especially during islanding operations [3]. The power exchange between the two sides of the grid is achieved through the bidirectional AC/DC converter which adheres to the power-sharing control strategy [4, 5].

An economic-based optimal distribution control strategy was introduced to reduce the power losses of parallel bidirectional power converters [6]. A two stages algorithm was employed to accomplish the objectives. A dedicated adaptive voltage controller was deployed in the first stage while an optimal distribution scheme was used in the second stage. A new switching lookup table based on the active and reactive power deviation was proposed in [4]. The algorithm achieved an enhanced power-sharing capability of the bidirectional converter. The issues of unbalanced AC voltage and current and the occurrence of DC ripple in three-phase bidirectional converters were mitigated by a multimode control strategy [7]. By regulating the voltage and current using the negative-sequence impedance of the converter, the research achieved ripple-free and balanced power transformation. Authors in [8] suggested a four-leg sinusoidal converter to resolve the problem of AC power ripple injected into the DC bus. The designed converter ensured a balanced operation while maintaining a smaller size, lower production cost, and longer lifetime than other utilized converters.

An economic droop-based controller was developed to guarantee the efficient and cost-effective operation of a bidirectional power converter in a Microgrid [1]. Power-sharing issues were addressed by the decentralized controller while different droop characteristics were implemented on both sides of the Microgrid. The research in [3] explored the three modes of islanded Microgrid Operation. Because of their hierarchical architecture, authors proposed the implementation of droop controllers to manage the Microgrid, especially with high penetration of DGs. The emulation of inertial response using PV solar panels and battery systems was considered for islanded Microgrids [9]. The oscillations and deterioration of grid performance caused by pulsed loads were examined in the research and significantly mitigated by utilizing DC resources and droop controllers.

In this research, a grid-supporting controller based on droop behavior is proposed to maintain the power-sharing between the AC and DC sides of a Microgrid. The controller consists of two levels of operation. At the primary level, the frequency and voltage are managed, while the second-level controller is deployed to track the active and reactive powers while eliminating deviations not tackled by the primary controller. It is assumed that there are two loads in the studied Microgrid, one is a critical DC load while the other is a dynamic three-phase AC load. The DC side of the grid incorporates PV solar cells and battery systems which are exploited to service the critical DC load and enhance the performance of the AC dynamic load. Unlike other research in this field, a third level of the decision-making control algorithm is proposed to isolate the AC side of the Microgrid from the DC side based on certain operating conditions. The parameters of the grid-supporting controller and the two DC/DC controllers of the PV and battery systems are tuned using the particle swarm optimization method and multi-objective cost function. The developed control scheme is required to maintain the stability of voltage and frequency of the AC side when the dynamic load changes and ensure that the DC load has adequate access to the required operating power.

In the next section, the general design of the studied Microgrid will be presented, while the proposed control scheme synthesis will be discussed in section (3). Section (4) addresses the implementation of the designed controllers to the Microgrid system. Conclusion and future work will be provided in section (5).

Microgrid Structure

In this section, the architecture of the studied Microgrid is presented, and the parameters of each part of the power system are illustrated. Figure (1) demonstrates a general overview of the Microgrid, and the control mechanism applied to the bidirectional power converter. On one side of the converter, the DC Microgrid consists of PV solar system, battery system, and critical (15 kW) load. On the other side of the bidirectional converter, a three-phase AC dynamic load is connected. Voltage and frequency of the load are carefully manipulated by the control system which regulates the shared power between the two sides. A high-level control algorithm was employed to toggle the DC power connector that enables the isolation of the DC side.

A. Power station and distribution network

The power station is represented as a (3.125 MVA) synchronous generator with a diesel engine regulator which internally regulates the governor model. The power station provides a constant voltage of (25 KV) with a constant frequency of (50 Hz). A power step-down transformer is then utilized to drop the voltage from (25 KV) to (400 V) normal grid operation level. An RLC branch is included to induce harmonic filtering capabilities.

B. Three-phase AC dynamic load

A three-phase dynamic load was utilized to test the viability of the proposed control system to load and grid variations. Assuming balanced currents, the active and reactive powers are represented as follows:

$$P(s) = P_0\left(\frac{V}{V_0}\right)^{np}\frac{1+T_{p1}s}{1+T_{p2}s}; \quad (1)$$

$$Q(s) = Q_0\left(\frac{V}{V_0}\right)^{nq}\frac{1+T_{q1}s}{1+T_{q2}s}, \quad (2)$$

where P_0 and Q_0 represent the initial values of active and reactive power respectively, V_0 is the initial positive sequence, V is the positive sequence voltage, nq and np are exponents that control the load type whether is linear or nonlinear. The time constants T_{p1} and T_{p2} control the dynamic of the active power, while similarly the time constants T_{q1} and T_{q2} control the dynamic of the reactive power. The following table exhibits the values for each parameter.

Table 1

Dynamic load parameters

Parameter	Value
P_0	10^3 W
Q_0	10^3 VAR
np	1.3
nq	2
V_0	[0.994...11.8]
T_{q1}, T_{q2}, T_{p1}, T_{p2}	[0.001, 0.01, 0.001, 0.01]

C. Bidirectional Power converter

This converter manages the shared power between the two sides of the Microgrid. A voltage source converter VSC model was used to emulate the converter where the internal switches are controlled by controller generated PWM signals. It exerts a significant influence on the performance of connected resources since it regulates the amount of power being extracted from the DC side and injected into the AC side of the Microgrid.

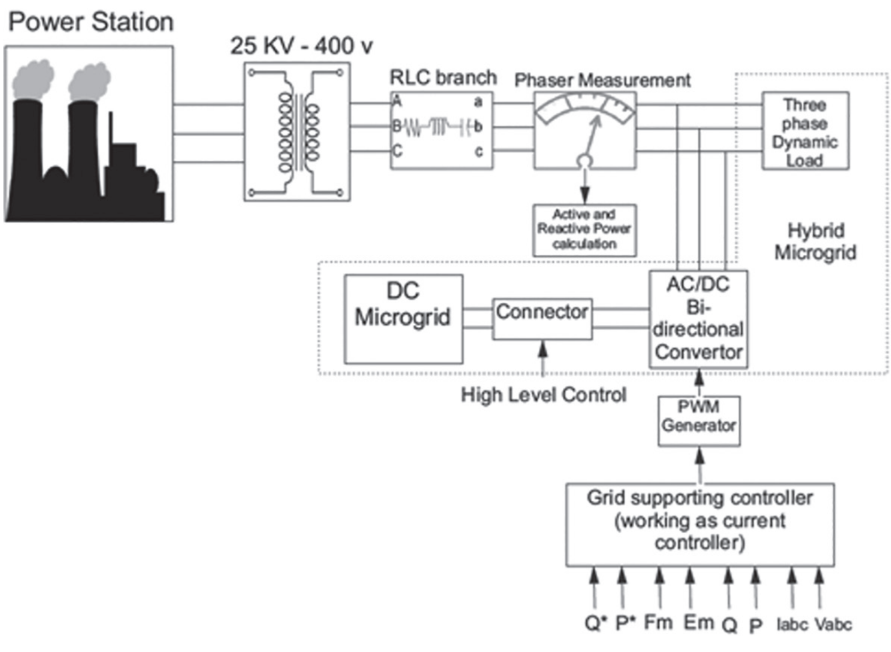

Fig. 1. Structure of the studied Microgrid

D. DC Microgrid (DC side of the hybrid Microgrid)

During the grid-tide operation, the DC system is considered a part of the hybrid Microgrid which enables it to share resources with the AC side. However, when the disconnection signal is initiated, the DC system will be completely isolated from the AC side and will act as a separate Microgrid. Figure (2) illustrates the structure of the DC sub-Microgrid. A boost converter with a maximum power point tracking MPPT technique is used to link the (10 kW) PV array to the DC system [10]. While the battery system utilizes a bidirectional DC/DC converter for the similar reason. Dual current and voltage control techniques are used to properly maintain the operation of the battery converter. The critical function of the DC load must be maintained by the DC converters, and the power of the DC side of the Microgrid is required to be adequate for the uninterruptable operation.

Controller Scheme Design

In this section, voltage and frequency controllers are developed for the hybrid Microgrid. Load variations, disturbances, and isolation of DC generators are some of the typical challenges that must be tackled by the utilized controllers. Therefore, an optimized performance grid-supporting droop controller is proposed for regulating the power-sharing process managed by the bidirectional converter. Furthermore, a high-level controller is deployed to protect the critical operation of the DC side by disconnecting both sides of the grid and preventing the depletion of resources.

A. Grid Supporting Controller

Droop controllers have been efficiently implemented in maintaining the balance between active and reactive powers which inductively stabilize voltage and frequency [11]. The hierarchical structure of such controllers enables them to respond on different levels and with different sampling rates. The primary and secondary droop controllers are demonstrated in fig. (3) where the secondary controllers are associated with delay. In the figure, the controller generates voltage and frequency error signals and passes them through an LPF before applying them to the droop control scheme. The effect of the desired active and reactive powers (P, Q) is, then, imposed by comparing them to the measured ones (P^*, Q^*). The equation of the anti-windup PID controller implemented to overcome the saturated control signal is as follows [12]:

$$u(t)=K_p e(t)+K_i\int e(t)dt+K_d\frac{de(t)}{dt}+K_b\int\left(u(t)-u^{Sat}(t)\right)dt, \quad (3)$$

where u^{Sat} is the saturated output of the PID controller. On the other hand, the two regulators in fig. 3 are realized by (PI) controllers and current limitation function that produce both (I_{dref}, I_{qref}). The current regulator function adheres to the following equations [13]:

$$U_d = V_d + I_d R - I_q L + \dot{I}_d L; \quad (4)$$

$$U_q = V_q + I_d L + I_q R + \dot{I}_q L \quad (5)$$

where R and L are the parameters of the converter filtering components, while U_d and U_q are the converter voltages in the (d-q) domain. These voltages are then transformed into the (abc) domain and supplied to the PWM generator.

B. Particle Swarm Optimization (PSO) algorithm

This algorithm belongs to the metaheuristics intelligent optimization methods that are being implemented to solve complicated engineering design problems. The PSO algorithm can provide a simplistic solution to a sophisticated design problem based on the provided performance index. It emulates an intelligent search method that utilizes several particles moving in a hyper-dimensional plane [14]. The location of these particles corresponds to the actual design parameters to be adapted and optimized. The general scheme of the PSO algorithm utilized in this research is illustrated in [14,15]. The algorithm was deployed to obtain the sixteen parameters of the dual droop controllers and the two regulators demonstrated in fig. 3. The employed performance index is formulated as:

$$Per_{indx}=\left(400-E_m\right)+\left(50-F_m\right)+\sum(\forall P_{DC}<15\ \text{Kw}), \quad (6)$$

where P_{DC} is the power of the DC side of the Microgrid.

C. High-level Isolation controller

The key objective of this controller is to preserve the operation of the DC side of the Microgrid from being jeopardized by the extensive depletion of battery resources. This controller checks the operating requirements and invokes the disconnection command

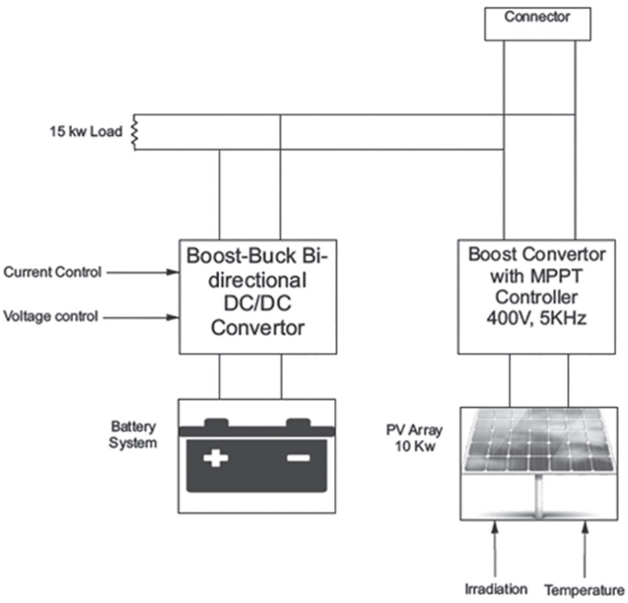

Fig. 2. DC Sub-Microgrid

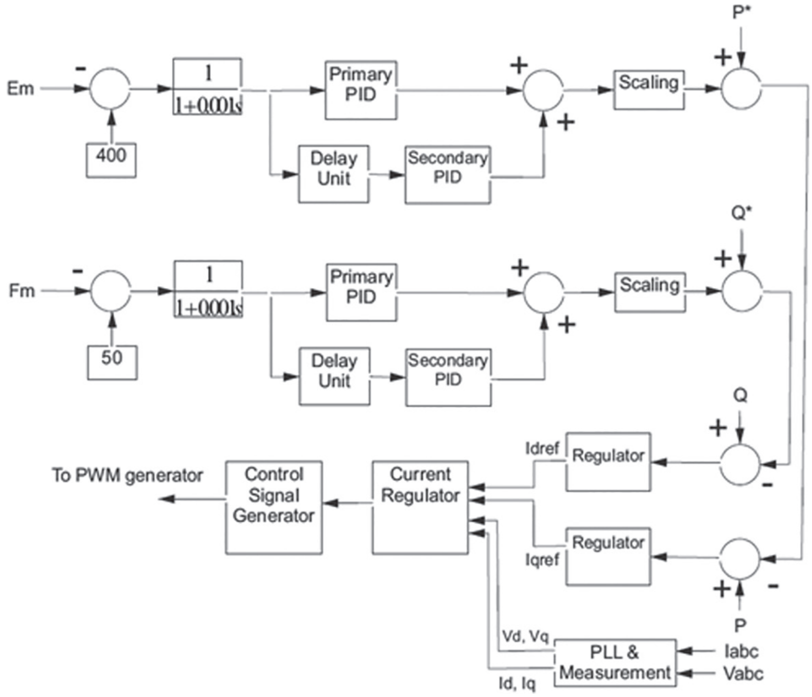

Fig. 3. Grid supporting control scheme

shown in fig. 2. Figure (4) demonstrates the structure of this high-level controller where the logic operator (NOR) is implemented to combine different isolation conditions. This disconnection signal is initiated when the battery SoC drops to less than (40%) or deterioration in the power quality is recorded for a significant period. Another way to invoke the disconnection of the DC sub-grid is by activating the operator disconnection command (ODC). The operator may choose to separate the DC side based on power predictions or weather forecasting.

Simulation and Results

The studied Microgrid and the proposed control system are developed in MATLAB/SIMULINK environment. The irradiation and temperature fed to the PV solar panel are assumed to be variable. This indicates that the power requirements of the Microgrid cannot be indefinitely sustained by relying on the PV system since the produced power is less than the maximum designed capacity. The nominal operation of the critical DC load requires an uninterruptible supply of (15 kW) with approximately (10 A) of consumed instant current. The PSO algorithm was deployed to tune the gains of the grid-supporting droop controller and the DC side controllers separately. Figure (5) shows the minimization of the cost function which was conducted in an off-line fashion.

A. AC/DC Power Sharing

In this mode, the power is exchanged between two sides of the Microgrid while the grid-supporting controller mitigates disturbances and regulated voltage and frequency deviations. It is assumed that the system is initialized at zero power where the conserved DC resources are exploited to rapidly regulate the system to the nominal operating point. Figure (6) demonstrates the response of the AC dynamic load. The slight fluctuations in the voltage level are caused

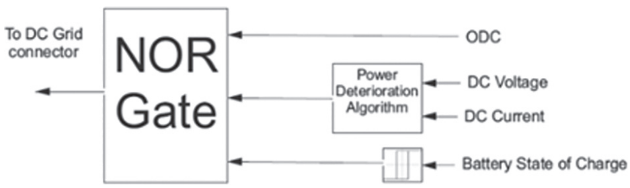

Fig. 4. High-level isolation algorithm.

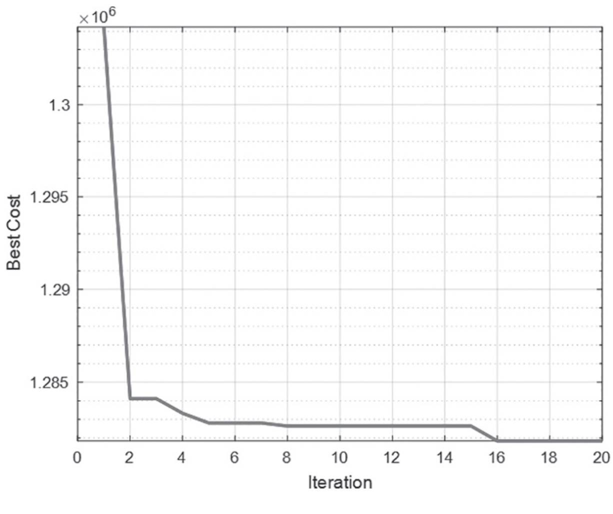

Fig. 5. PSO algorithm implementation for grid supporting controllers

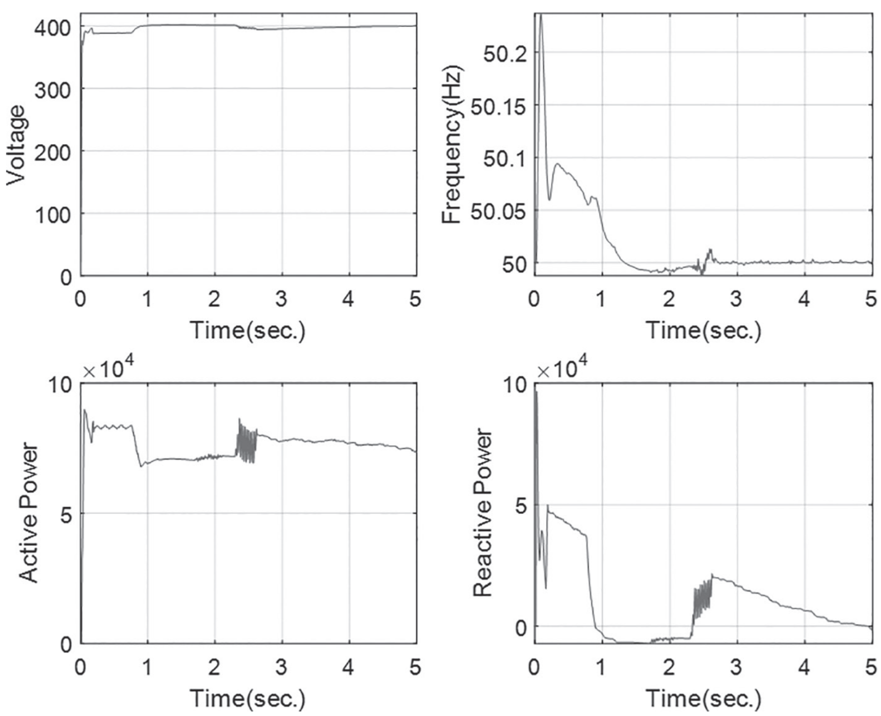

Fig. 6. Response of the AC side of the Microgrid in power-sharing mode

by the load power variations while the frequency was rapidly regulated to the nominal value. Although active and reactive powers are varying as seen in the figure, the controller limits their fluctuation and drives them to a nominal value that complies with the requirements.

Figure (7) illustrates the power level at the DC side of the grid along with the consumed instant and mean currents. The increased power production on the DC side is directly associated with the mitigation of dynamic load changes on the AC side. The controller acts to inject regulating power to the AC side while maintaining the operation of the (1500 V, 15 kW) critical DC load. Thus, power-sharing is achieved, and critical load nominal operation is served. It is worth mentioning that the employed battery system retains a maximum capacity of (200 Ah) which is used to support the hefty load operation.

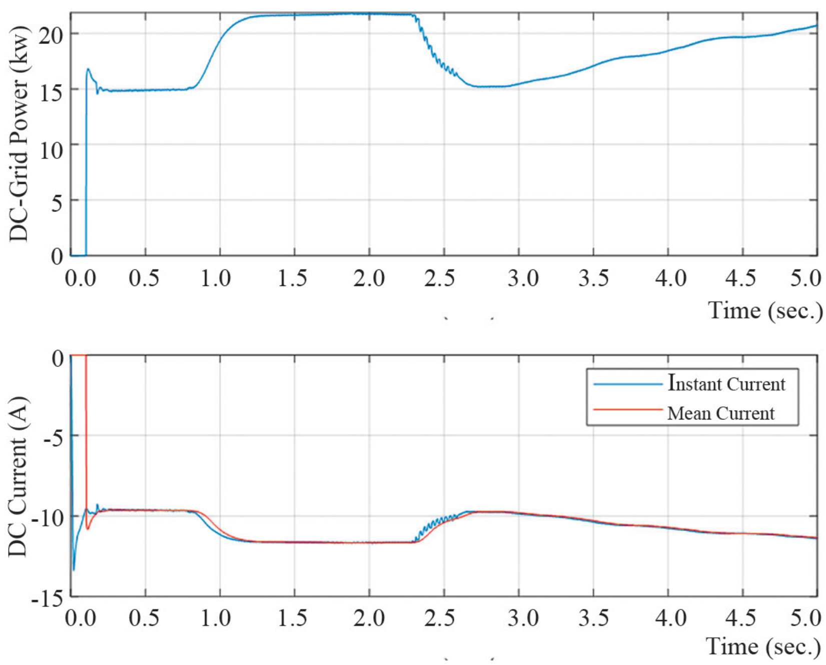

Fig. 7. Response of the DC side of the Microgrid in power-sharing mode

B. DC Islanding Mode

It is assumed that the ODC command is activated, and the DC side of the grid is initially isolated from the rest of the Microgrid. In this case, the DC sub-grid is controlled by the MPPT and the battery controllers. PV solar panels and battery systems are used to sustain the operation of the islanded part while the bidirectional converter is idle with no power exchange. Figure (8) demonstrates the behavior of the three-phase dynamic load which is connected directly to the utility grid. As anticipated, the performance of the voltage response suffers keenly from slow regulation while the frequency response encounters overshot which is larger than the one experienced in the previous mode. Moreover, the responses of the active and reactive power are unconfined to a certain limit which indicates the loss of control over these variables.

The response of the DC side of the grid is shown in fig. (9). The DC controllers swiftly stabilized the power of

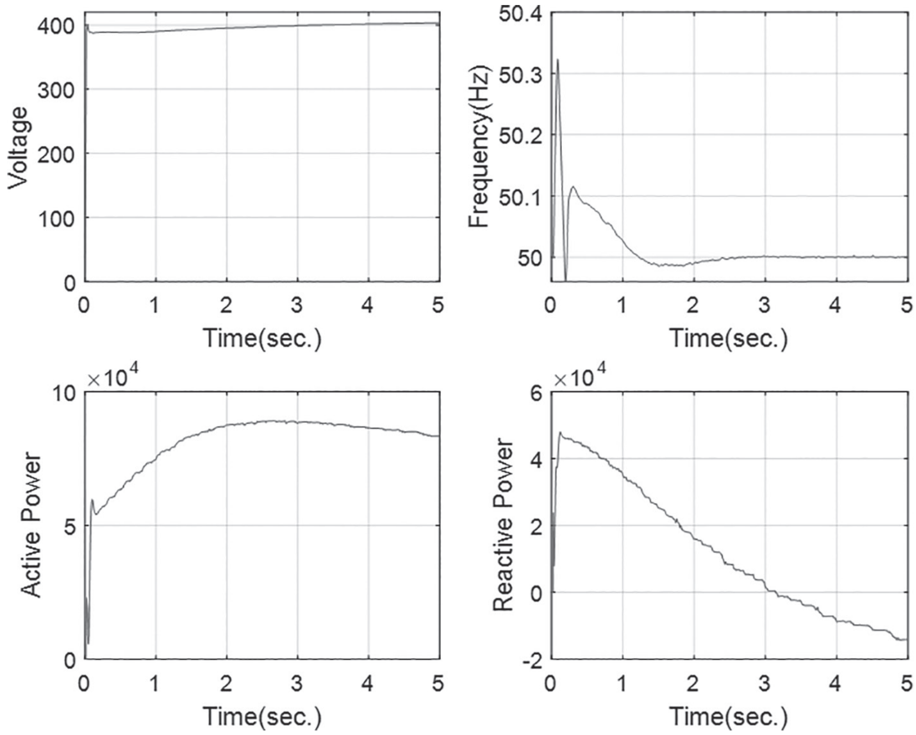

Fig. 8. Response of the AC side of the Microgrid in DC islanding mode

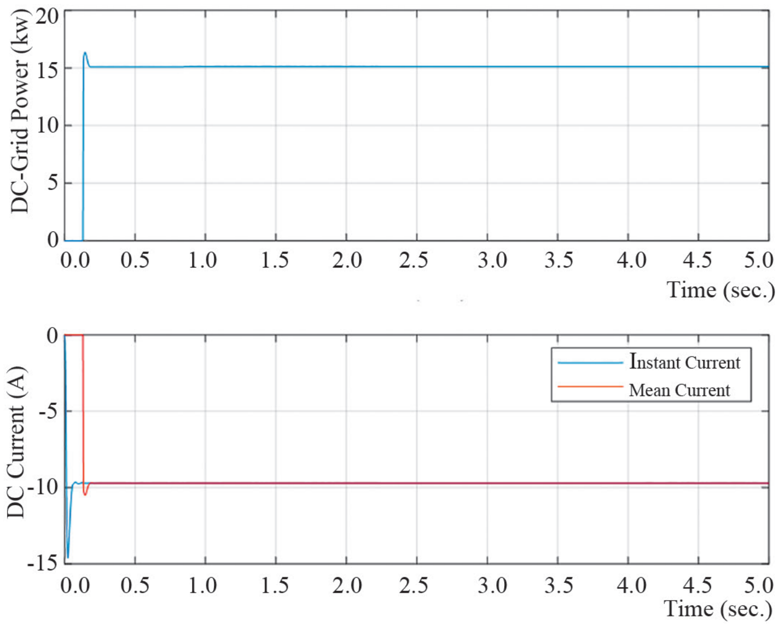

Fig. 9. Response of the DC side of the Microgrid in DC islanding mode

the DC grid while the DC currents reached a steady state value less than (10 A). The obvious advantage of this mode is that the critical DC load operation is maintained while the DC resources are preserved.

Conclusion and Future Work

In this research, an optimized grid supporting controller based on the droop characteristic was developed and deployed to operate an AC/DC bidirectional converter controlling the power-sharing of a functioning Microgrid. A PSO algorithm was implemented over the proposed scheme to tune the gain parameters and achieve the required performance. The controller maintained the power-sharing between the AC and DC grid resources and successfully ensured a satisfactory performance of both AC and DC loads. For securing the operation of the critical DC load and preventing the depletion of the battery resources, a high-level isolation controller was proposed and implemented. The function of the controller is to disconnect the DC side from the rest of the Microgrid when a deterioration of the DC load operation is sensed. Both modes of operation for the power system were simulated, and the validity of the control scheme has been confirmed.

This work is part of a larger project to examine the performance of various resources when connected to a Microgrid. Multiple industrial loads with sophisticated characteristics are to be considered in future research. Furthermore, the integration of other distributed generators (DGs) and their resulting effect will be studied. More specialized power-sharing controllers like the distributed-decentralized controllers are advised, in that case, due to their organizational advantages.

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