Controllable AC/DC Integration for Power Quality Improvement in Microgrids

Abdulkerim KARABİBER
Bingol University, Faculty of Engineering and Architecture, Department of Electrical and Electronics Engineering, Turkey
akarabiber@bingol.edu.tr

***Abstract*—Renewable energy sources can be connected to utility grids by using AC and DC integration methods. The AC integration is a practical and cost-effective method thanks to its simple structure; however, its power quality protection is weak. The DC integration method provides high power quality to microgrids owing to extra AC/DC voltage conversion, but its power efficiency is lower than that of the AC integration method. This paper presents a controllable AC/DC integration method combining the advantages of both AC and DC integration methods. In the proposed method, AC integration is activated to provide high integration efficiency at times when the power quality of the utility grid is suitable. At other times when the power quality of the utility grid is unsuitable, DC integration is activated to improve the power quality of the microgrids. The proposed method was modeled and tested using Matlab/Simulink simulation environment. In the model, voltage sag and current harmonic distortion were used as destructive effects for the electrical energy of the utility grid. Results indicate that transitions between AC and DC integration modes are reliable in terms of voltage and current standards.**

***Index Terms*—energy efficiency, harmonic distortion, microgrids, power quality, renewable energy sources.**

I. INTRODUCTION

In the recent decades, a large proportion of the world's energy demands are met by fossil fuels. Fossil fuels are unsustainable energy sources since they are harmful to the environment and have a limited amount. As an alternative to fossil fuels, renewable energy sources (RESs) are clean and inexhaustible energy sources. However, RESs were not reliable and cost-effective sources to meet big scale energy demand until the last decade. Nowadays, RESs can be installed in different scales owing to advanced technology; therefore, the use of RESs is becoming widespread in electricity generation, industry and transportation sectors day by day. This recent shift in practice encourages researchers and governments to develop new strategies to benefit more from RESs in the future.

Studies on the technical potential of RESs show that RESs will generate more energy in the future. According to the World Energy Outlook (2017), about two-thirds of global power investments will be devoted to RES plants by 2040 and RESs will be the cheapest energy sources for many countries [1]. China, the largest energy consumer in the world, generated 8% of its energy from renewable sources in 2006. This rate is expected to be 15% in 2020 and 40% in 2040 [2]. The EU has set strict RES targets to reduce greenhouse gas (GHG) emissions and the speed of global warming [3]. Not only the developed but also the developing countries such as Pakistan [4] and Turkey [5] focus on RES investments to meet increasing electricity demand from clean and sustainable energy sources.

Most RESs generate electricity in the DC voltage, but the existing electric power systems and devices are compatible with the AC voltage. Various techniques are utilized to provide a harmony between RESs and electricity distribution grids. In general, RESs are connected to electrical power systems using the AC and DC integration methods. In the AC integration method, only an inverter is needed for the DC/AC power conversion between a RES and utility grid. The AC integration has, therefore, a simple topology and its efficiency is higher than that of the DC integration. On the other hand, extra control units are required in the AC integration method for power quality issues such as frequency stability, phase angle adjustment and voltage regulation. Furthermore, the AC integration method has no healing effect on utility grid energy and may reduce the power quality of the main grid.

In the DC integration method, the energies of RESs and utility grid are mixed on a DC bus. For this purpose, the AC voltage of the utility grid is converted to the DC voltage which is compatible with the DC bus. This voltage conversion decreases efficiency of the energy supported by the utility grid. However, the controllability and efficiency of energy from RESs increase since only one inverter is employed for all RESs. The studies [6-8] demonstrate that the DC integration improves the power quality and energy reliability of microgrids. Nowadays, DC microgrids are used to support sensitive loads such as communication buildings and data centers. The increase in the use of DC voltage indicates that the DC integration method will be used more in the future microgrids.

The AC and DC integration methods have pros and cons in terms of power quality and efficiency. One of these methods is chosen based on microgrid features and at the expense of advantages of the other. This problem can be solved by using an approach which combines AC and DC integration methods. This paper presents a controllable AC/DC integration method which enables AC and DC energy mixing in a single power control system. The proposed method aims to protect the power quality of microgrids from destructive effects of utility grid by activating the DC integration mode. At other times when utility power is reliable, the AC integration is activated to increase the efficiency of the microgrid. Thanks to the contribution of the proposed method, RES integration mode can be changed under variable loading conditions to improve the power quality and increase the efficiency in microgrids.

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The rest of the paper is organized as follows. The second part presents a literature review on the improvement of power quality in electrical distribution grids. The third section introduces the RES integration techniques which are employed in practice. The fourth section describes the proposed method. The simulation results are indicated and discussed in the fifth section. Finally, the conclusion is presented in the last section.

II. Literature Review

There are numerous studies in the literature to improve power quality in conventional electrical power systems and modern microgrids. In [9], a hierarchical control method was proposed to reduce voltage disturbances in AC microgrids. In this method, a general case and different locations were gradually evaluated by considering the harmonics and unbalance distortions of load bus. The results show that the effectiveness of the method is different in various power scenarios. In [10], a distribution static compensator was designed with neural fuzzy network to reduce the harmonics of grid current and improve the voltage of DC-link. The method reduces the harmonic distortion by up to 4% for the tests performed under the variation of nonlinear and linear inductive load.

Various inverter control techniques were proposed to enhance power quality in microgrids. In [11], extension active-reactive power method was presented to decrease harmonics and adjust power factor. In [12], fractional order controller was employed to filter harmonics with active filters. In [13], a dual inverter topology was utilized to compensate unbalanced and nonlinear loads. The results demonstrate that the method maintains DC-link voltage when sudden changes occur in load. In [14], shunt active power filter was employed to regulate DC-bus voltage of a standalone hybrid system. The results illustrate that the proposed method has a better harmonic compensation performance more than the conventional configuration.

Power quality disturbances must be properly classified to ensure the reliability of the energy in electricity distribution grids. In [15], rule based extreme learning machine method was utilized to detect and classify the disturbances. This method manages to classify the disturbances with accuracy between 94% and 99%. In [16], wavelet transforms and decision tree classifier were employed to detect power quality events. In this study, online and offline configurations were tested to recognize the disturbances in a conventional power system. In [17], an automatic power quality recognition system was designed with the combination of transform technique and neural network. According to the previous studies, the authors achieved to reduce the processing time required for power quality disturbances.

Distribution static compensators (DSTATCOM) can be utilized to overcome power quality issues such as improving power factor, filtering harmonics and balancing nonlinear loads. In [18], DSTATCOM based voltage regulator was designed to adjust DC bus voltage and active power flow in distribution grids. In [19], an algorithm based on affine projection was improved to estimate the required grid current from the measurement data of unbalanced loads. This approach aims to increase the speed of convergence and to compensate the harmonic distortions by using DSTATCOM. In [20], adaptive control algorithm was improved to manage on-grid photovoltaic system including DSTATCOM. The power quality protection performance of the proposed method was demonstrated by the tests performed under different weather and load conditions.

Energy storage systems can be employed to improve power quality in microgrids. In [21], a supercapacitor storage system was utilized to control DC bus voltage of a microgrid. In this study, simulation and experimental results are presented to illustrate the effectiveness of the proposed method. In [22], second-order sliding method was developed to control the power flow of a hybrid energy storage system. In this work, the proposed method and classical PI method were compared in terms of harmonics suppression and dynamic performance. Hybrid energy storage systems can be used to provide ancillary service in conventional and smart grids. In [23], power control strategies were presented to manage hybrid storage systems for power quality enhancement in microgrids.

III. RES Integration

RESs can be installed using grid-connected and standalone configurations. Standalone RES systems have no electrical connection with utility grid, therefore, energy storage devices are required to provide a balance between generation and demand of electricity. Standalone RES systems are employed in microgrids which are far from utility grids. The operation of grid-connected RES systems is compatible with utility grids. The extra energy of microgrid demand is sold to utility grid and the remaining energy of microgrid generation is completed by utility grid. Grid-connected systems are more cost-effective and more efficiently than standalone systems because energy storage devices are not needed. Therefore, grid-connected RES configurations are mostly preferred in distribution and transmission electrical grids.

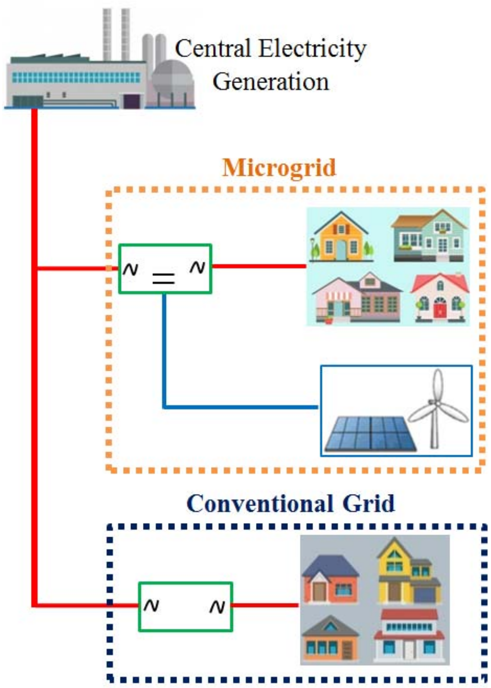

Figure 1. A RES AC integration block diagram

In conventional electrical power systems, electricity is generated in central plants and transmitted in high voltage. Distribution stations step down the high voltage to mid-voltage for end users. RESs can be integrated to conventional power systems through distribution or transmission lines. Fig. 1 indicates a RES AC integration block diagram for a microgrid. A conventional grid is supplied from central plants via an AC/AC converter (transformer). A microgrid is supplied from RESs and utility grid via an integration unit. The AC or DC integration method can be used to manage the energy of the microgrid. However, the output voltage of the integration unit has the same electrical characteristics as conventional electrical loads.

A. AC Integration

The studies [24-25] compare AC and DC microgrids in terms of cost, efficiency, reliability, controllability and maintenance. In general, AC integration is more suitable for the existing power systems; however, the use of DC integration is increasing with the developments of DC technology. Fig. 2 shows a common configuration for the AC integration method. Each of RESs or a RES group is connected to utility grid via an inverter. Inverters continuously track utility grid voltage to synchronize integration and distribution line voltages. Thanks to this feature, any point in electricity distribution line can be used for RES integration. A power switch (S) is utilized to disable the utility grid from the micro grid when RES electricity generation is efficient for the load.

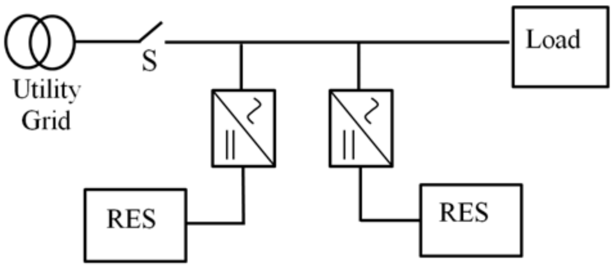

Figure 2. The block diagram of AC integration method for RESs

In AC integration method, all power adjustments increasing RES efficiency are made in inverters. The output power of RESs depends on weather conditions and electrical power features. Inverters track the maximum power point by adjusting the output voltage of RESs. The electrical characteristics of RESs power should be compatible with distribution systems in terms of frequency, phase angle and voltage amplitude. Otherwise, RESs reduce the power quality and damage the whole electrical power system. Inverters collect and evaluate the information about the main power system to provide electrical synchronization between utility grid and RESs. RESs power can be shared out among loads and energy storage devices according to power flow strategies implemented by the controller of inverters. Furthermore, inverters are employed to overcome power quality issues such as harmonic distortion and reactive power requirement. These tasks reveal that the inverter has a key role in increasing the reliability and efficiency of RES systems in AC integration method.

The *P-Q* theory is a suitable method to generate reference current for the inverters used in AC microgrids. In this method, the active (*P*) and reactive (*Q*) powers can be calculated as follows.

$$P = u_{ga} i_{La} + u_{gb} + i_{Lb} + u_{gc} i_{Lc} \tag{1}$$

$$Q = u'_{ga} i_{La} + u'_{gb} i_{Lb} + u'_{gc} i_{Lc} \tag{2}$$

u_{ga}, u_{gb} and u_{gc} are the grid voltages of a three-phase power system and lead u'_{ga}, u'_{gb} and u'_{gc} by 90°, respectively. i_{La}, i_{Lb} and i_{Lc} are the load currents. The reference currents can be calculated as follows.

$$\begin{bmatrix} i^*_{ga} \\ i^*_{gb} \end{bmatrix} = \frac{P_c}{\Delta} \begin{bmatrix} u'_{gb} - u'_{gc} \\ -(u'_{ga} - u'_{gc}) \end{bmatrix} \tag{3}$$

$$i^*_{gc} = -(i_{ga} + i_{gb}) \tag{4}$$

where

$$\Delta = (u_{ga} - u_{gc})(u'_{gb} - u'_{gc}) - (u'_{ga} - u'_{gc})(u_{gb} - u_{gc})$$

and P_c is the command of required power. Finally, the reference currents of the inverter are defined as follow.

$$\begin{aligned} i^*_{ca} &= i_{La} - i^*_{ga} \\ i^*_{cb} &= i_{Lb} - i^*_{gb} \\ i^*_{cc} &= i_{Lc} - i^*_{gc} \end{aligned} \tag{5}$$

The *P-Q* theory is an easy and effective current control method that reduces the complexity of the power control in microgrids.

B. DC Integration

RESs are replaced in utility grids to meet consumers' energy demand. In microgrids generating self-sufficient electricity, consumers meet most of their energy from RESs and have no need for utility energy except in emergencies such as overloading and system faults. In self-sufficient microgrids, utility grid is utilized as a backup system, and the DC integration is the method of choice to mix the energy of RESs [6-7]. Fig. 3 indicates a common block diagram for DC integration method. Microgrid is connected to utility grid with a bidirectional AC/DC converter for energy transfer. The energies of RESs and utility grid are mixed on the DC bus. The power switch (S) is used to disconnect the utility grid for standalone operation of micro grid. Load is supplied by conventional distribution voltage (AC) using an inverter.

DC integration method has several advantages and disadvantages compared to AC integration method. Its most important advantage is that DC energy mixing facilitates the electrical integration of different energy sources because it is free from reactive power and frequency. Thanks to this feature, power losses and computational loads, which are made for integration, are reduced. In the DC integration method, DC bus voltage is converted to AC voltage by a single inverter; therefore, different energy sources act as a single energy source, and the power quality of the microgrid increases. On the other hand, the efficiency of the DC integration is lower than that of the AC integration because the voltage of the utility grid is additionally converted for DC voltage mixing. The DC integration is therefore not the method of choice in microgrids which meet most of their energy needs from utility grids.

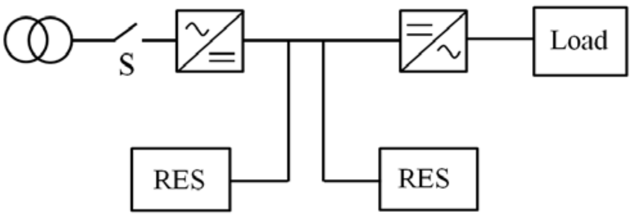

Figure 3. The block diagram of DC integration method for RESs

The output voltage of RESs (U_{RES}) varies with weather conditions. In general, a DC/DC converter is used to fix the voltage of RESs and acquire stable DC bus voltage (U_{bus}) for DC energy mixing. U_{bus} is adjusted with Equation 8.

$$U_{bus} = \frac{1-D}{D} U_{RES} \tag{6}$$

D is duty cycle rate of semiconductor switches in the power converter. Feedback controller is employed to determine the value of D by evaluating the desired U_{bus} and instant measurement of U_{RES}.

IV. CONTROLLABLE AC/DC INTEGRATION

Fig. 4 shows the main blocks of the controllable AC/DC integration method. Load and utility grid are assumed to be compatible with AC distribution voltage. Controllable AC/DC integration method contains an AC/DC rectifier and a DC/AC inverter, as in the DC integration method. The inverter converts the DC bus voltage to the AC voltage of the utility grid. The AC/DC rectifier is employed to support the DC bus voltage when electricity generation of the microgrid is insufficient to meet the demand. The microgrid may include one or more RESs, and their energy mix on the DC bus. Thanks to S1 and S2 switches, one of the AC and DC integration modes can be the method of choice depending on the energy management strategy used in the microgrid.

Table 1 tabulates the integration modes of RESs based on S1 an S2 switch states. In the case of s_1=s_2=0, the microgrid is in standalone mode and has no any electrical connection with the utility grid. In standalone mode, electricity generation of RESs is sufficient to meet the demand and the extra power of RESs is charged by energy storage devices which can be connected to the DC bus. In the case of s_1=1 and s_2=0, the microgrid is in the AC integration mode, in which the inverter converts the DC bus voltage to the AC voltage. In the case of s_1=0 and s_2=1, the microgrid is in DC integration mode, in which the energies of RESs and the utility grid are mixed on the DC bus. In the case of s_1=1 and s_2=1, the micro grid is in transition mode. The transition mode is not a steady state working condition. It occurs only in the transition process between the AC and DC integration modes.

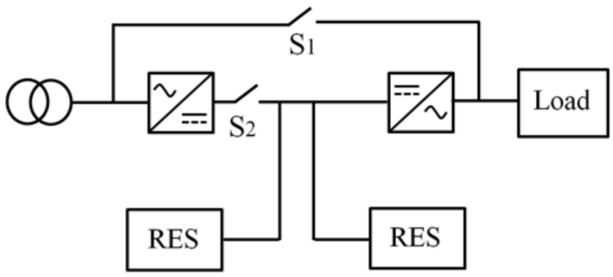

Figure 4. Main blocks of controllable AC/DC integration method

TABLE I. INTEGRATION MODES BASED ON THE SWITCH STATES

s_1	s_2	Mode
0	0	Standalone
1	0	AC Integration
0	1	DC Integration
1	1	Transition

A microgrid generally operates in standalone mode when it generates its own self-sufficient energy. For this purpose, the coefficient r_p is defined in Eq. 7 to determine microgrid working conditions in standalone or integration mode. r_p is the rate between power demand (P_{demand}) and RESs electricity generation ($P_{generation}$). P_{demand} and $P_{generation}$ are measured in integration center, so there is no need to consider the power losses caused by electricity transmission. r_p=1 means that power generation and demand are equal. Similarly, r_p<1 means that power generation is higher than demand and r_p>1 means that demand is more than power generation in the microgrid. Electrical loads can be changed suddenly; therefore, the reference value of r_p used in the integration activation control should be less than 1 to protect the power quality of the microgrid. In addition, the r_p value should be close to 1 for the activation of AC integration mode during the hours when the microgrid generates sufficient power. In this study, the reference value of r_p is 0.9. In other words, when r_p is higher than 0.9, the AC or DC integration is activated to support the microgrid.

$$r_p = \frac{P_{demand}}{P_{generation}} \tag{7}$$

In the controllable AC/DC integration method, different parameters can be used as controller inputs to activate the AC or DC integration mode. Controller inputs are defined depending on the purpose of the integration activation strategy such as power quality protection, increasing system efficiency and power supplies management. In this study, the AC or DC integration mode is activated to protect the power quality of the microgrid when the power quality of the utility grid is weak. Fig. 5 indicates the flowchart of the controllable AC/DC integration method that was designed by using Matlab/Simulink simulation environment. r_p, voltage sag (U_{sag}), total harmonic distortion of current (I_{thd}) and DC bus voltage (U_{bus}) are employed as controller inputs. As a result of the logical process, the AC or DC integration mode is activated by the controller.

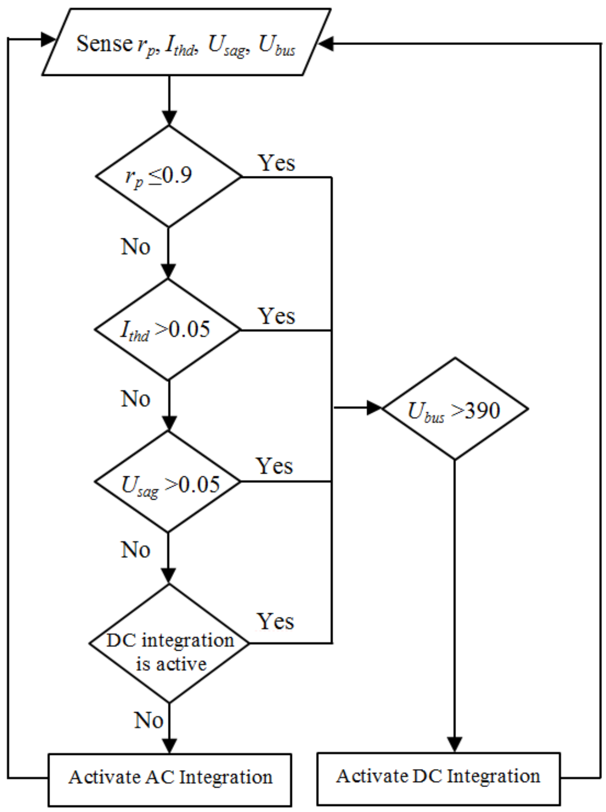

Figure 5. Flowchart of controllable AC/DC integration method

The AC integration provides higher power efficiency than the DC integration; therefore, the former is the mode of choice by the proposed method when the utility grid has robust electrical energy. The DC integration mode is activated to protect the power quality of the microgrid in the case when the utility grid has weak power quality. As mentioned in Section 2, the recommended upper limit of U_{sag} and I_{thd} in modern electrical power systems is 5%. In the proposed method, the DC integration mode is activated when Ithd or U_{sag} is higher than 5%. However, the DC bus should have a stabile voltage characteristic so that the DC integration can be active. In this study, the steady state voltage of the DC bus is 400 V, however, the DC bus voltage falls below 400 V at the times when the electricity generation by RESs is insufficient to meet the energy demand of the microgrid. Therefore, the DC bus voltage must be greater than 390 volts for the DC integration mode to be active. If the microgrid operates in integrated mode and the DC bus voltage is less than 390 volts, then the AC integration mode is activated by the controller.

The inverter converts the DC bus voltage to the AC voltage, which is compatible with utility energy, therefore, the AC and DC integration modes can be active simultaneously and this does not negatively affect the power stability of the microgrid. However, the concurrent activation of the AC and DC integration modes can increase the voltage stress on the power converters. For this reason, the concurrent activation is prevented by using the NOT command of the DC activation as an input variable of the AC activation. In this way, the AC integration mode is absolutely deactivated at the time when the DC integration is active.

V. CASE STUDY

A microgrid where PV panels were utilized as a RES was designed using Matlab/Simulink simulation to test the controllable integration method. The power converters were modeled with PWM control technique. Furthermore, dynamic switching was employed to design variable electrical loads. The details of the blocks were presented in our previous study [26]. The simulation model was run in possible integration formats separately to determine the effective operation of the power components. Fig. 6 shows the DC bus voltage (inverter input) and load voltage occurring in the case when solar system feeds the load independently of the grid. The DC bus voltage reaches 400 V, which is the reference voltage, in 0.2 seconds. Once the DC bus voltage becomes stable, the load voltage reaches 390 V (phase to phase) peak value with a robust AC form characteristic. For detailed analysis, the sinusoidal curve of the load voltage between 0.4 and 0.5 seconds is also given in Fig. 6. The voltage characteristics shown in Fig. 6 indicate that the designed system operates efficiently in standalone mode.

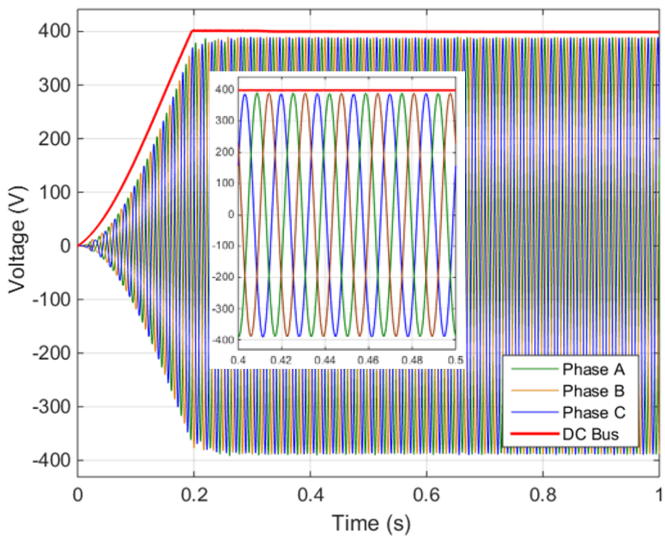

Figure 6. DC bus and load voltages in the standalone mode

One possible operating mode of the system is the AC integration mode. In the AC integration method, an imbalance between power generation and demand may adversely affect the frequency of the system and cause fluctuations in the system voltage. This study uses frequency and voltage stability to measure the efficiency of the integration method. In the AC integration mode, the renewable energy sources were connected to the grid with no harmonic distortion using the AC integration technique in order to determine the performance of the simulation model. Fig. 7 shows the variation of the system frequency depending on the variable load, indicating that the frequency change is negligible and within the limits of stability under different loads. This result shows that the AC integration method is useful under variable load conditions.

In the DC integration method, whether the main grid supports the microgrid or not depends on the DC bus voltage. Fig. 8 shows the activation of the main grid depending on the DC bus voltage. The bus voltage starts to fall when the demand is more than the PV generation. When the DC bus voltage drops to 390 V, the DC integration becomes active and allows the main grid to support the micro grid. After the grid support starts, the drop rate of the DC bus voltage slows down and begins to increase after the transition period of the power converters. Once the bus voltage reaches 390 V again, the grid support is inactivated, and the system is allowed to operate in standalone mode. One important point to note about the DC integration method is that after the grid support is activated, the DC bus voltage continues to drop due to the time it takes for the power converters to be stable. Considering the transition process, the reference voltage used to activate the DC integration should be higher than the lower limit of the inverter input voltage.

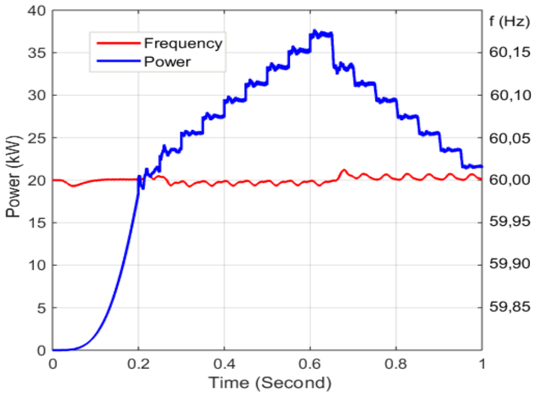

Figure 7. Variation of system frequency for variable load conditions

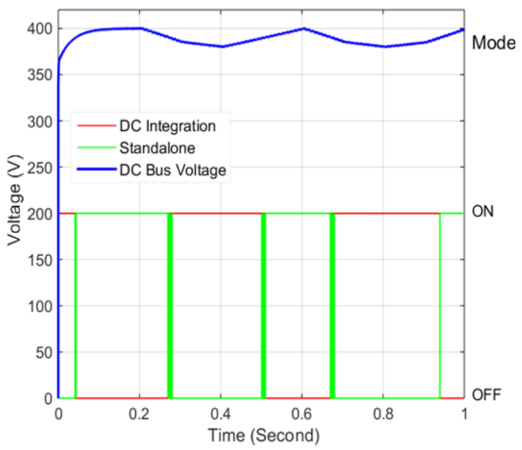

Figure 8. Activation of DC integration mode depending on DC bus voltage

In the controllable integration method, the RES is connected to the main grid by the AC integration method under normal grid conditions (I_{thd} <0.5 and U_{sag} <0.5). The activation of the AC integration is controlled by the r_p and by the DC bus voltage. When power generation does not meet the demand (r_p<0.9) and during the stabilization of the DC bus voltage (U_{bus}<390), the micro grid operates in the AC integration mode. Fig. 9 shows the AC integration transitions depending on the r_p and DC bus voltage. Although PV electricity generation is higher than the demand, the microgrid is in AC integration mode because the bus voltage is less than 390 V at the beginning of the simulation. After the DC bus voltage raises to 390 V, the microgrid switches to standalone mode. The system switches back to the AC integration mode after the r_p rises over 0.9. In the last part of the simulation, the microgrid works in AC integration mode because the DC bus voltage has a stable structure and r_p is greater than 0.9. These and previous results show that the microgrid operates efficiently under normal grid conditions and provides reliable energy to the load during the transitions between the AC and DC integration modes.

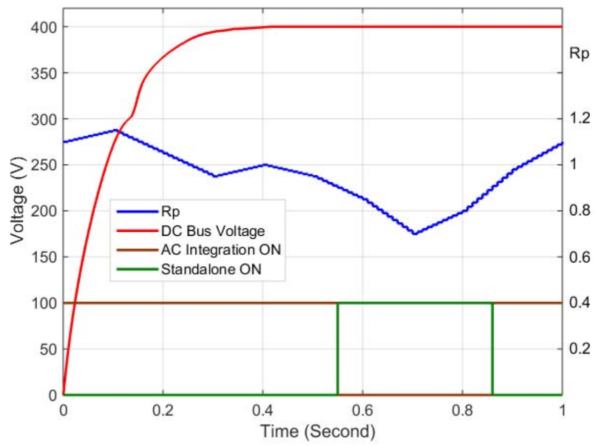

Figure 9. Activation of AC integration mode depending on r_p and DC bus voltage

Power loss in the AC integration method is less than that in the DC integration method. Therefore, the system favors the AC integration method under normal conditions in the controllable integration method. On the other hand, the DC integration method can provide higher quality power to the load despite harmonics, distortions and voltage sags on the grid. When the power quality drops below the reference values, the microgrid passes from AC to DC integration. Fig. 10 shows AC-DC integration transitions due to the harmonic distortions in utility grid current. Harmonic distortion in utility grid current increased to 15% between 0.50 and 0.72 seconds, as shown in Fig. 10. After the harmonic distortion in utility grid current exceeds 5%, the micro grid starts to operate in the DC integration mode. Once the DC integration mode is active, the harmonic distortion in the current of the microgrid decreases rapidly. During the DC integration mode, the harmonic distortion in utility grid current does not adversely affect the microgrid current. After the harmonic distortion in utility grid drops below 5%, the microgrid switches back to the AC integration mode. Current curves show that the microgrid is not adversely affected by the transitions between the AC and DC integration modes.

Voltage sag is a common problem which causes drops in power quality in electrical grids. Voltage sag is observed when the demand is exceeded by the power capacity of the grid or when the voltage calibrator is not compatible with the grid structure. Devices running under voltage sag do not operate well and they overheat due to excess current drawn. Fig. 11 shows the transitions between the AC and DC integration modes depending on voltage sag. The voltage sag of about 9% occurs in the grid voltage between 0.40 and 0.71 seconds. Once the voltage sag increases to 5%, the grid switches to the DC integration mode. In the first moments when the voltage sag occurs, the microgrid voltage drops as well, however, the voltage sag in the microgrid decreases and becomes zero after the grid switches to the DC integration mode. As long as the DC integration is active, the microgrid is not negatively affected by the voltage sag that occurs in the main grid. The microgrid operates in the AC integration mode once the grid voltage drops below 5%.

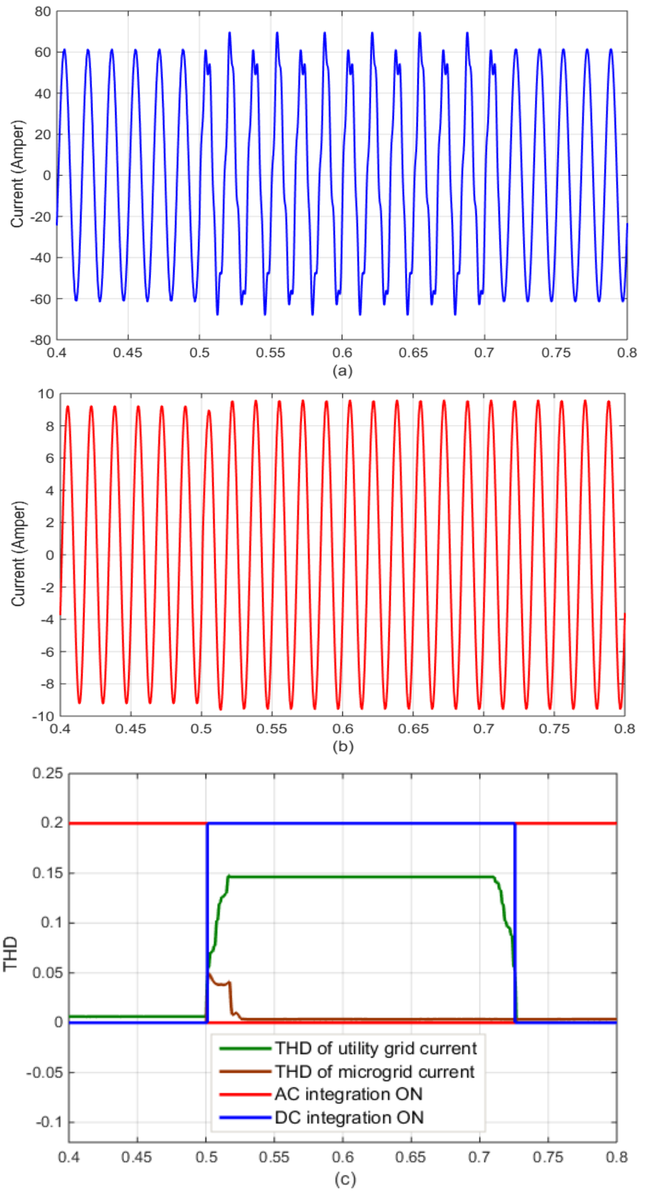

Figure 10: a) The current of utility grid; b) The current of microgrid; c) Activation of AC and DC integration modes depending on THD of utility grid current

Three microgrids with the same electrical characteristics were separately connected to utility grid by using AC integration, DC integration and AC/DC integration techniques to compare the methods in terms of power quality performance. Harmonics were employed to distort the power quality of utility grid energy. Fig. 12 shows the results of THD rates occurred in the microgrids. The THD of the microgrid using DC integration method is close to zero during the simulation time. This means that DC integration method provides high power quality protection for microgrids against the disruptive power events occurred in main grids. The THD of the microgrid using AC integration method is close to the THD of utility grid. The THD of the microgrid using the proposed method is same with the THD of AC integration method because AC integration mode is active when the THD of utility grid is smaller than 5%. After the THD of utility grid is bigger than 5%, the THD of the proposed method closes to zero since the DC integration mode was activated.

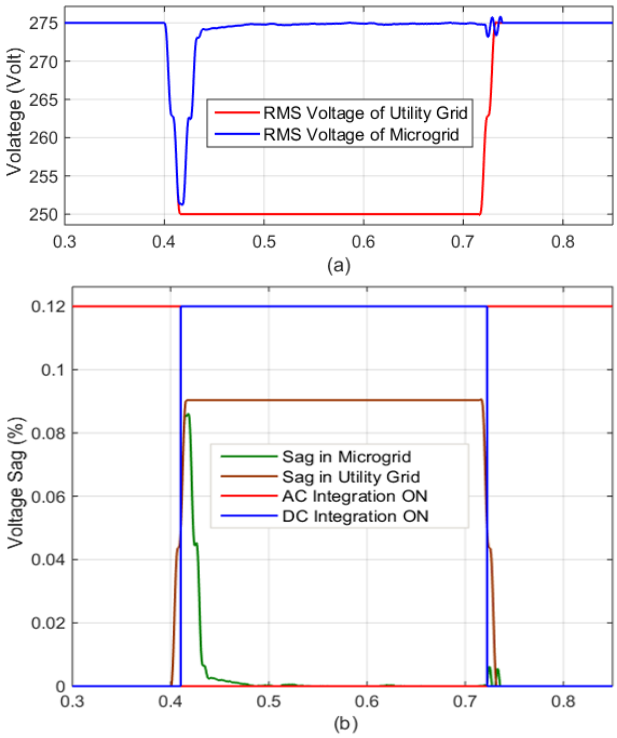

Figure 11: a) The RMS voltages of utility and micro grids; b) Activation of AC and DC integration modes depending on the voltage sag of utility grid

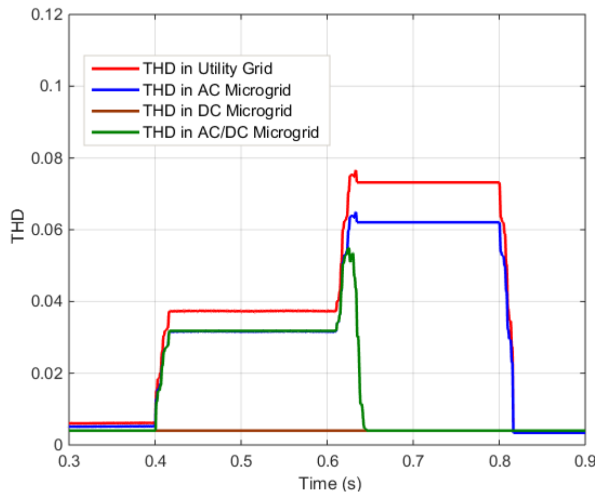

Figure 12. THD of the microgrid currents for different integration modes

The results illustrate that the proposed integration method protects the microgrid against the drawbacks reducing the power quality of the main grid. In addition, the power quality of the microgrid is within the recommended limits during the transitions between the AC and DC integration modes. This study addressed voltage sag and current harmonic distortion as destructive effects. The controllable integration method can also be used against other problems that reduce power quality such as voltage fluctuation and current harmonic distortion. To do this, it is sufficient to set the limit values for disturbances depending on microgrid sensitivity.

The efficiency of RES integration methods varies depending on the technology used in power converters. Today, the maximum efficiency for AC/DC inverters and DC/AC rectifiers can reach %96 and %99, respectively [27-28]. The efficiency of the proposed method equals to the efficiency of inverter when AC integration mode is active. In other case, when DC integration mode is active, the power losses occurred in the inverter and the rectifier are considered to find the efficiency of the proposed method. Furthermore, the investment cost of the proposed method is equal to DC integration method as the same power components are required to perform the methods.

VI. Conclusion

RES integration has a significant role in providing high power quality and high energy efficiency in microgrids. The AC and DC integration methods are commonly used in the existing grids including RES systems. The methods are superior to each other in such aspects as power quality and energy efficiency. This study presents the AC/DC integration method which combines the advantages of the AC and DC integration methods. To test the proposed method, a mid-scale microgrid system including RESs was modeled in Matlab/Simulink. Different power issue scenarios were simulated in the model to analyze the transitions between the integration modes and steady state operations of the microgrid. The results reveal that the controllable AC/DC integration method improves the power quality of the microgrid against power quality disturbances occurring in the utility grid.

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