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Advanced Active Power Conditioner to Improve Power Quality in a Micro Grid

Prof.A.N.Malleswara Rao
Professor, Dept Of EEE, RMCE,Hyderabad

Abstract: *This paper presents a three-phase Active Power Conditioner to improve power quality in micro grids based on renewable energy. A micro grid is a weak electrical grid which can be easily subject to disturbances. The Active Power Conditioner (APC) presented in this paper acts as an interface between renewable energy sources and the AC bus of a micro grid and uses an improved control strategy, which makes possible to inject energy in the micro grid, compensate the current harmonics and correct the power factor. Moreover, the proposed control strategy allows the line current at the point of common coupling (PCC) to be balanced and sinusoidal even when the load is unbalanced. Consequently, the voltage at the PPC becomes balanced. Simulation results show the validity of the innovative control strategy.*

Keywords: *Active Power Conditioner, Micro grids, Renewable Energy, Current control*

I. Introduction

Technological advances in power electronics have created opportunities for the renewable sources to be exploited in different configurations. The power electronic interface allows renewable sources to be connected with the distribution grid or interconnected with other renewable and non-renewable generators, storage systems and loads in a micro grid [1]. A micro grid is different from a main grid system which can be considered as an unlimited power so that load variations do not affect the stability of the system. On the contrary, in a micro grid, large and sudden changes in the load may result in voltage transient of large magnitudes in the AC bus. Moreover, the proliferation of switching power converters and nonlinear loads with large rated power can increase the contamination level in voltages and currents waveforms in a micro grid, forcing to improve satisfy more stringent harmonics standards. A possible solution to overcome the above mentioned drawback is to use the APC as a power interface between the renewable energy sources and the AC bus of the micro grids.

The APC has proved to be an important alternative to compensate current and voltage disturbances in power distribution systems [2], [3]. Different APC topologies have been presented in the technical literature [4], but most of them are not adapted for s applications. The attention will be mainly focused on the innovative control strategy, which allows injecting energy, compensating the current harmonics, correcting the power factor and balancing the supply voltage at the PCC. The validity of the control strategy has been proved through many simulation tests using Simulink from MATLAB.

II. Active Power Conditioner

Recently, a variety of non-linear loads such as rectifiers, battery chargers, motor drivers and UPS (Uninterruptible Power Supply) have been widely used in a distribution power system. These non-linear loads can generate a great amount of harmonic currents injecting into the distribution power system. This may result in overheating transformers, fluctuations of rotary electric machines, voltage distortion of utility power and damage to electric equipment in the distribution power system. In order to improve the problems with the harmonic pollution, many harmonic control standards, such as IEEE519-1992, IEC1000-3-2, and IEC1000-3-4 etc., have been established. Many countries have therefore enforced these control standards. Therefore, how to solve the harmonic problems is an important topic in today's power system worldwide. On the other hand, many of the loads in the distribution power system are inductive (inductor-type) loads that result in lagging power factor of reactive power. To compensate the lagging reactive power, the distribution power system must further supply reactive power to the loads in addition to real power. Accordingly, it would be disadvantageous that the efficiency of the distribution power system is lowered and the voltage regulation in the load side is poor. Furthermore, it would be also disadvantageous that a larger capacity of the power transmission of the distribution power system is required.

As has been explained above, linear loads with a resistance characteristic are preferred in the distribution power system. However, the linear resistance loads only consume real power in the distribution power system and may not produce harmonics. Traditionally, passive electric components are used to form a power conditioner applied in the distribution power system so as to operate the loads for creating a linear resistance characteristic. For example, a passive power filter can reduce harmonic currents produced by the non-linear loads, and improve power factors. A power capacitor set is also used to reduce reactive currents produced by inductive loads. However, there exist some problems with using the passive power conditioner applied to create the linear resistance characteristic. For example, the passive power filter may cause drawbacks of serial/parallel resonance, injection of neighbouring harmonic and lower filtering effect; and the power capacitor may also cause drawbacks of serial/parallel resonance, injection of neighbouring harmonic, unvaried reactive power compensation and incapability of linear adjustment. In order to solve the problems with the passive power conditioner for the AC load, the active power conditioner comprising power electronic components, as shown in Fig.4.1, has been developed. Traditionally, the active power conditioner (so-called active power filter) includes a DC power capacitor, a power converter and a high-frequency filtering circuit. In this case, the active power conditioner electrically connects with a load in parallel and operates therewith. A non-linear characteristic of the load can be adjusted and shifted to a linear resistance characteristic by the active power conditioner which can eliminate reactive current and harmonic currents of the load . Accordingly, a sinusoidal waveform of a current supplied from a power source has phase identical with those of voltages of the power source. Consequently, the characteristic of the load can be conditioned to be a linear resistance characteristic.

In operation, the active power conditioner detects a load current, a power source voltage and a DC capacitor voltage that are calculated in a complicated process to generate a compensation current signal for sending to a feedback controller. An output current of the power converter is further detected and sent to the feedback controller. The feedback controller processes the compensation current signal and the output current of the power converter by means of a closed-loop control. Accordingly, the output current of the power converter can be adjusted to respond to changes of the compensation current signal. Although it would be advantageous that the active power conditioner is, however, successful in reducing harmonics and creating a linear resistance characteristic, constructions of the control circuit are complicated. Hence, there is a need for improving the active power conditioner for the AC loads.

The present invention intends to provide an active power conditioner for AC load characteristics. This active power conditioner can generate a driving signal for a power converter by detecting a voltage of a DC power capacitor for processing a closed-loop control and detecting a current of a power source for processing a feed forward control. In the present invention, calculation of the compensation current signal and detection of the output current of the power converter are not required. In this manner, the active power conditioner can adjust a non-linear load to be performed a linear resistance characteristic, reduce the harmonic and reactive current and simplify the control circuit. The primary objective of this invention is to provide an active power conditioner connecting with a load in parallel and operating therewith. A non-linear characteristic of the load is adjusted to be a linear resistance characteristic and reactive currents are eliminated. The combination of the active power conditioner with the load can be considered as a linear resistance characteristic, observed from a power source side.

III. Power Quality

3.1 Power Quality Problems

Power quality problems as: ‘Any power problem that results in failure or misoperation of customer equipment manifests itself as an economic burden to the user, or produces negative impacts on the environment.’

- The power issues which degrade power quality include:
    - Power Factor
    - Harmonic Distortion
    - Voltage Transients
    - Voltage Sags or Dips
    - Voltage Swells
- Power quality can be improved through:
    - Power factor correction,
    - Harmonic filtering,
    - Special line notch filtering,
    - Transient voltage surge suppression,
    - Proper earthing systems.

3.2 The Benefits Of Power Quality

Power quality in the container terminal environment impacts the economics of the terminal operation, affects reliability of the terminal equipment, and affects other consumers served by the same utility service.

3.3 ECONOMIC IMPACT

The economic impact of power quality is the foremost incentive to container terminal operators. Economic impact can be significant and manifest itself in several ways:

3.3.1 Power Factor Penalties

Many utility companies invoke penalties for low power factor on monthly billings. There is no industry standard followed by utility companies. Methods of metering and calculating power factor penalties vary from one utility company to the next. Some utility companies actually meter kVAR usage and establish a fixed rate times the number of kVAR-hours consumed. Other utility companies monitor kVAR demands and calculate power factor. If the power factor falls below a fixed limit value over a demand period, a penalty is billed in the form of an adjustment to the peak demand charges.

3.3.2 System Losses

Harmonic currents and low power factor created by nonlinear loads, not only result in possible power factor penalties, but also increase the power losses in the distribution system. These losses are not visible as a separate item on your monthly utility billing, but you pay for them each month.

3.3.3 Power Service Initial Capital Investments

The power distribution system design and installation for new terminals, as well as modification of systems for terminal capacity upgrades, involves high cost, specialized, high and medium voltage equipment. Transformers, switchgear, feeder cables, cable reel trailing cables, collector bars, etc. must be sized based on the kVA demand. Thus cost of the equipment is directly related to the total kVA demand. As the relationship above indicates, kVA demand is inversely proportional to the overall power factor, i.e. a lower power factor demands higher kVA for the same kW load.In the absence of power quality corrective equipment, transformers are larger, switchgear current ratings must be higher, feeder cable copper sizes are larger, collector system and cable reel cables must be larger, etc. Consequently, the cost of the initial power distribution system equipment for a system which does not address power quality will most likely be higher than the same system which includes power quality equipment.

3.4 Equipment Reliability

Poor power quality can affect machine or equipment reliability and reduce the life of components. Harmonics, voltage transients, and voltage system sags and swells are all power quality problems and are all interdependentHarmonics affect power factor, voltage transients can induce harmonics, the same phenomena which create harmonic current injection in DC SCR variable speed drives are responsible for poor power factor, and dynamically varying power factor of the same drives can create voltage sags and swells. The effects of harmonic distortion, harmonic currents, and line notch ringing can be mitigated using specially designed filters.

3.5 Environment

No issue might be as important as the effect of power quality on our environment. Reduction in system losses and lower demands equate to a reduction in the consumption of our natural resources and reduction in power plant emissions. It is our responsibility as occupants of this planet to encourage conservation of our natural resources and support measures which improve our air quality.

IV. Active Power Conditioner Topology

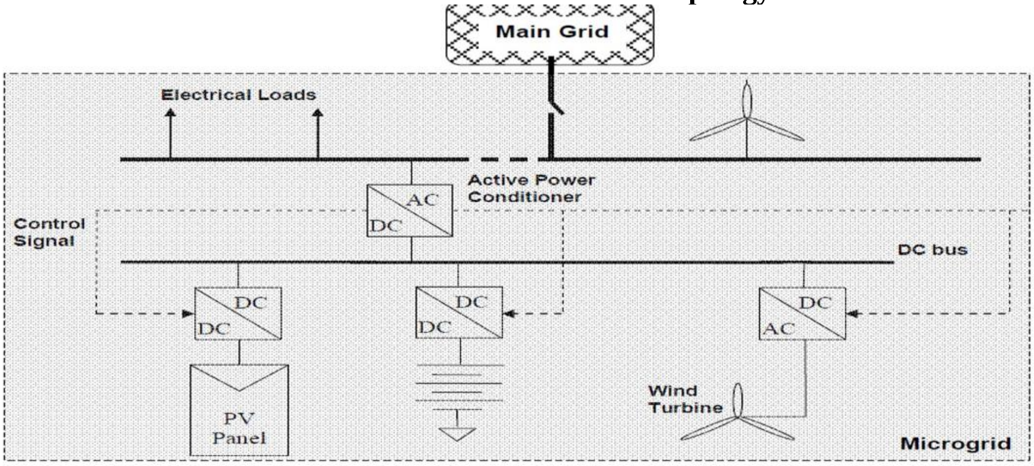

Figure: 4.1 APC for Micro grid applications

4.1 Active Power Conditioner Topology

Generally, four-wire APCs have been conceived using four leg converters [5]. This topology has proved better controllability [6] than the classical three-leg four-wire converter but the latter is preferred because of its lower number of power semiconductor devices. In this paper, it is shown that using an adequate control strategy, even with a simple three-leg four-wire system, it is possible to mitigate disturbances like voltage unbalance. The topology of the investigated APC and its interconnection with the micro grid is presented in Fig. 4.2. It consists of a three-leg four-wire voltage source inverter. In this type of applications, the VSI operates as a current controlled voltage source. In order to provide the neutral point, two capacitors are used to split the DC-link voltage and tie the neutral point to the mid-point of the two capacitors. This topology allows the current to flow in both directions through the switches and the capacitors, causing voltage deviation between the DC capacitors.

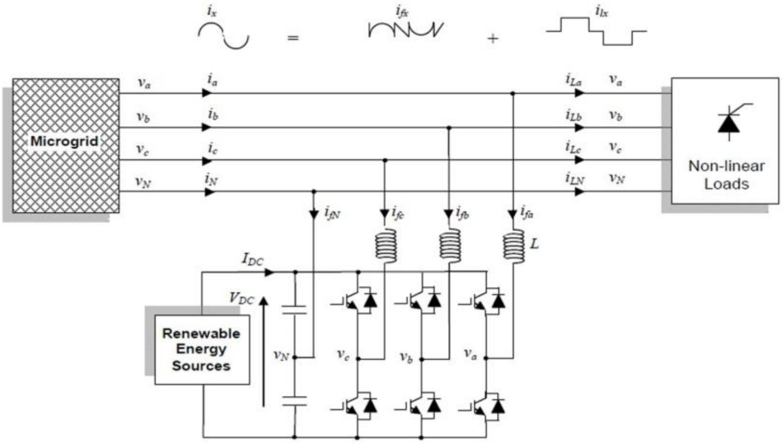

Figure: 4.2 Connection for APC for Micro grid

$$i_{fa} + i_{fb} + i_{fc} = i_{fN} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where:

ifa, *ifb*, *ifc* are phase APC currents and *ifN* is the APC neutral Therefore, the total DC voltage will oscillate not only at the switching frequency but also at the corresponding frequency of the neutral current. As shown in [2], if the current control is made by hysteresis, the above mentioned drawback can be limited with a dynamic offset level added to both limits of the hysteresis band. For the investigated topology presented in Fig. 2, the current at (PCC) is: $i_x = i_{lx} + i_{fx} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$

where:

*i*x, *il*x, *if*x are the side current, the load current, and the APC current respectively. The *x* index points the *a*, *b* and *c* current phases. The instantaneous load current is: 1

$$i_{lx} + i^{1}_{lx} + i_{lxk} + i_{lxq} \dots\dots\dots\dots\dots\dots\dots\dots (3)$$

where:

- i^{1}_{lx} the fundamental active current component;
- i_{lxk} the addition of current harmonics;
- i_{lxq} the reactive current component.

The three-phase APC current is given by:

$$i_{fx} = i^{1}_{fx} + i^{\sim}_{fx} \dots\dots\dots\dots\dots\dots\dots\dots .(4)$$

i^{1}_{fx}- The fundamental conditioner current component;

$i^{\sim}_{fx}$- The deforming component of the current. As shown in Fig. 2 the current drawn from the grid has to be sinusoidal and moreover, in phase with the voltage at PCC. Consequently, the control strategy for the APC has to be designed in order to ensure a sinusoidal wave for the grid current:

$$i^{1}_{lx} + i_{lxk} + i_{lxq} + i^{1}_{fx} + i^{\sim}_{fx} = i_x \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .(5)$$

The APC switches generate undesirable current harmonics around the switching frequency and its multiples. Considering the switching frequency of the APC sufficiently high, these undesirable current harmonics can be filtered with the LR passive filter.

V. Control of the Apc

5.1 Control Strategy

There are many ways to design a control algorithm for an APC [7] [8]. Generally, the controller design is made considering that the grid voltage at the PCC is balanced. In a micro grid, the supply voltage itself can be distorted and/or unbalanced. Consequently, the controller of an APC used to improve the power quality in the micro grid has to be designed according to the weakness of this kind of grid.

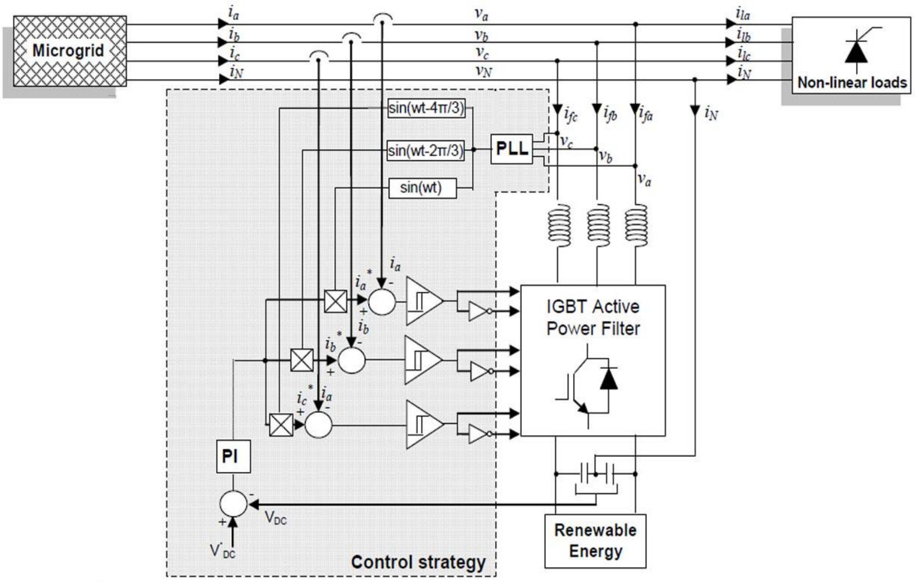

Figure: 5.1 APC control strategy

That makes the APC compensate the current of a non-linear load by forcing the micro grid side current to become sinusoidal and balanced (Fig. 5.1). The controller requires the three-phase grid current (i_a, i_b, i_c), the three-phase voltage at the PCC (v_a, v_b, v_c) and the DC-link voltage (VDC). As shown in Fig. 5.1, the sinusoidal waveform and the phase of the grid current reference (i_a*, i_b*, i_c*) comes from the line voltage thanks to a PLL. The magnitude of the same current is obtained by passing the error signal between the DC-link voltage (V_{DC}) and a reference voltage (V_{DC}*) through a PI controller. Using this magnitude and phase displacement of 120° and 240° respectively, the reference three-phase grid currents i_a*, i_b* and i_c* can be expressed as:

$$i^*_a = (pi)\sin\omega t \qquad \text{............(6)}$$

$$i^*_b = (pi)\sin\left(\omega t - \frac{2\pi}{3}\right) \qquad \text{.............(7)}$$

$$i^*_c = (pi)\sin\left(\omega t - \frac{4\pi}{3}\right) \qquad \text{..........(8)}$$

5.2 Switching Control

As shown in Fig.5.1, the hysteresis control has been used to keep the controlled current inside a defined band around the references. The status of the switches is determined according to the error. When the current is increasing and the error exceeds a certain positive value, the status of the switches changes and the current begins to decrease until the error reaches a certain negative value. Then, the switches status changes again.

Compared with linear controllers, the non-linear ones based on hysteresis strategies allow faster dynamic response and better robustness with respect to the variation of the non-linear load. A drawback of the hysteresis strategies is the switching frequency which is not constant and can generate a large side harmonics band around the switching frequency. To avoid this drawback, the switching frequency can be fixed using different solutions like variable hysteresis bandwidth [9] or modulated hysteresis [10].

VI. Simulation Results

To validate the proposed control algorithm, many simulations have been run in various operating conditions using Mat lab, SimPowerSystems toolbox. The investigated active power conditioner has been simulated with six IGBTs controlled by the system illustrated in Fig.5.1. All the parameters are shown in Table 1. During all the simulations, the power coming from the renewable energy sources is considered unvarying.

Table 5.1: Parameters of the APC

S No	Parameters	Values
1	AC voltage V_{abc} [V]	230
2	DC-link voltage (V_{dc})[V]	750
3	Inductor(L) [mH]	3
4	Capacitor (μF)	2000
5	Hysteresis Band [A]	0.5

The simulation results are grouped and presented according to the following power quality indicators: THD (Total Harmonic Distortion), power factor and unbalanced load.

6.1 Harmonic's compensation

During this case study, the APC is investigated using a three-phase diode bridge rectifier with a 60 Ω resistor in series with a 0.1 mH inductor at the DC side. The power delivered by the renewable sources is 3 kW and the load requires 5 kW. Fig. 6.1 shows the currents and supply voltage at the PCC. As can be seen, most of the current required by the load (i_l,$i_{abc}n$) is injected by the APC (renewable energies, if,$i_{abc}n$) and the balance comes from the micro grid, $i_{abc}n$. The current absorbed by the rectifier is not sinusoidal and has a THD of 30%. The frequency noise that can be observed on the APC current waveforms is due to the switching of the IGBTs.

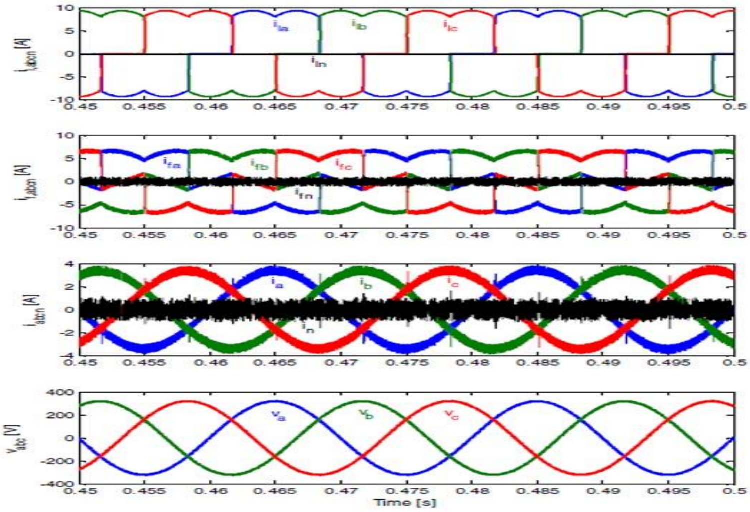

Figure: 6.1 Currents and voltage in the PCC during harmonics compensation test

The proposed control strategy allows the current $i_{abc}n$ on the micro grid side to be sinusoidal (Fig.4) with a THD of about 3% (Fig. 6.2). In the same Fig 6.2, it can be seen the THD of the load current (30%) and the voltage THD at the PCC which is 1.3%. The voltage THD is lower then the THD imposed by the EN 50160 Standard (THD<8%) [10].

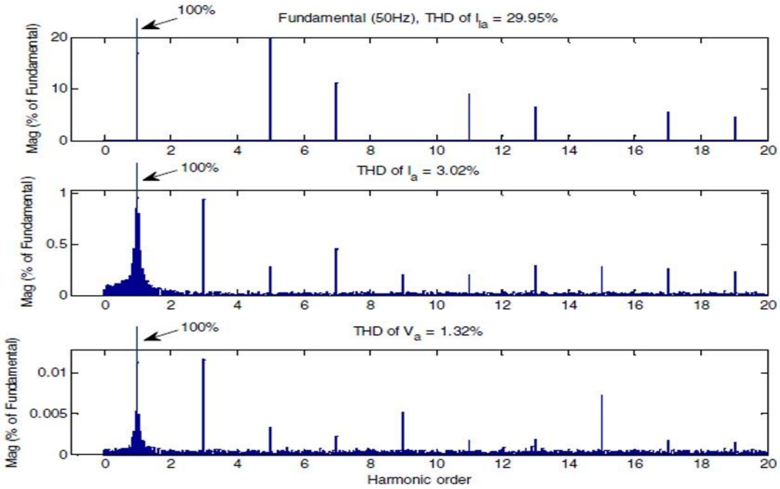

Figure: 6.2 THD of the micro grid side current and voltage

6.2 Power factor correction

The second case study shows the ability of the APC to compensate the power factor. The power factor can be controlled with capacitor banks, but in distorted conditions the results are poor and also the capacitor life is shorter.

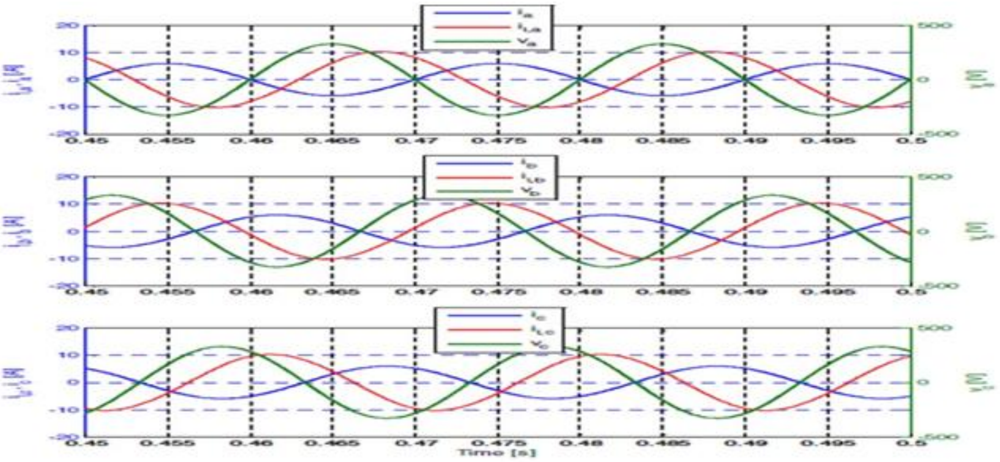

Figure: 6.3 Currents and voltage in the PCC during the power factor correction

For this case study, the load is composed by a three-phase inductor in series with a three-phase resistor and requires about 3kW active power and 4 kVAR reactive power. The power generated by the renewable sources is about 6 kW. Fig. 6.3 illustrates the load current, the micro grid side current and the supply voltage respectively at the PCC for each phase. As shown in the figure, the measured power factor between the load current and the supply voltage is 0.58. Thanks to the proposed control strategy, the APC is able to impose a unity power factor between the micro grid side currents and the supply voltage. The phase of the micro grid side currents is inverted relatively to the phase of supply voltages at the PCC because the power injected by the APC exceeds the power required by the load. Consequently, the surplus renewable energy is injected into the micro grid.

6.3 Unbalanced load

When several single-phase loads are unequally distributed on a distribution system, the fluctuating power required from each of these loads can cause unbalanced voltage in a weak power system. Under unbalanced conditions, the distribution system will incur more losses and heating effects and will be less stable. For this case study, the APC is used to compensate the unbalance induced by a resistive three-phase load.

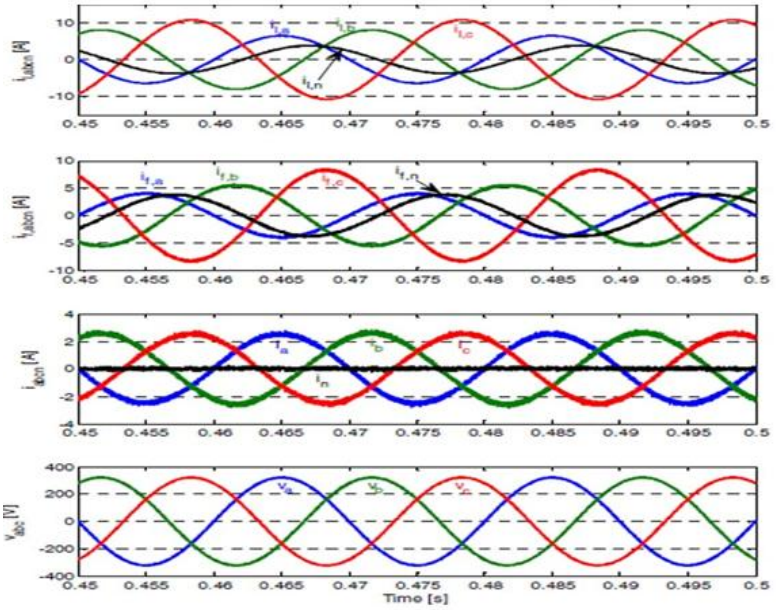

Figure: 6.4 Current and voltage at the PCC during unbalance load test

The phase *a* of the load is charged with 1050 W, the phase *b* with 1311 W and the phase *c* with 1749 W. The Fig. 6.4 shows the current and the voltage at the PCC. As shown in the previous section, the investigated APC is controlled such that the micro grid current required by the load ($i_{abc}n$) is sinusoidal and balanced. Consequently, the voltage in this point is also balanced. To quantify the level of the voltage unbalance, the percentage of negative sequence unbalance is expressed in accordance with the definition of the ‘‘degree of unbalance in three-phase systems’’ [11]. As shown in Fig.6.3, using the APC equipped with the proposed controller, the degree of the negative sequence unbalance is lower than 0.8%. It must be noticed that international standards admit unbalances lower than 2% [11].

VII. Conclusions

In this paper, an APC used to improve power quality in micro grids based on renewable energy has been presented. The APC is controlled using an innovative control strategy allowing the line current at the point of common coupling to be balanced and sinusoidal even when the load is unbalanced. The control of the three-phase line current enables the three-phase voltage balance at the PCC, allowing excellent regulation characteristics. Different case studies have been investigated with the APC simulated in the Mat lab Sym Power System and the simulations results have shown a good steady state. A prototype of the APC is being installed in order to test the feasibility of the control algorithm in real conditions.

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