SEAMLESS CONTROL OF DISTRIBUTED MULTI-CONVERTER SYSTEM WITH HIGH POWER QUALITY

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ABSTRACT

Robust control of inverter-interfaced distributed energy resource (DER) in a smart distribution grid is essential in order to facilitate flexibility of the grid. This paper presents a control structure for multi-converter system based on direct-current control and dynamic power sharing at the point of common coupling (PCC). The system includes two voltage source converters (VSCs) for grid interface of DERs and the active damping controller in the voltage control which is provided by the converter-interfaced load (CIL) for effective rejection of disturbances. On the other hand, wide band voltage control loop in both grid-connected and islanded modes is designed to improve the dynamic response of the system featuring power quality (PQ) improvement. The proposed scheme addresses a robust controller against interaction dynamics between active damping and current tracking controller in the presence of grid induced disturbances.

INTRODUCTION

One of the most important concerns in modern power systems is power quality (PQ) due to extensive use of power electronics and because of industrial loads, mostly arc furnaces, welding machines, uncontrolled diode rectifiers and thyristor switched devices. A simple and practical way to solve the problem is tuning single frequency passive filter [1] that is based on the resonant rejection of single harmonics. But, the recent methodology is active filtering that is provided by the series and shunt utilization of power electronic systems [2]. Grid connected distributed converters based on the high flexibility of voltage source converters (VSCs) have capability to enhance power quality by reducing harmonic effects [3].

Matrix converter interfaced PM machine in addition to reactive power compensation and power factor modification can improve the power quality and reduce the THD of the source current, up to power factor of the PM generator [4]. Besides uncontrolled rectifiers, converter-interfaced loads (CILs) can be source of harmonics if not controlled appropriately especially in case of transportation and automation. But, these loads in case of power control could be robust against non-sinusoidal non stationary currents, as well as voltage fluctuations.

The VSCs are tested and evaluated for active filtering and termed as shunt active filters [5] and the *p-q* theory is proposed for shunt active filtering in case of non-sinusoidal source current [6].

In this paper, controllable distributed energy resource (DER) is used as shunt active filter to eliminate harmonics from the source current in addition to supplying active power to the non-linear load. The extraction of the compensating signal is done in synchronous reference frame (SRF). The control methods based on SRF are very similar to the control methods based on *p-q* theory. For the power quality improvement an online harmonic detection is used for effective mitigation of dynamic, unbalanced and harmonic current disturbances. In respect to the interaction between converters, system dynamics are considered in the control system.

Due to the time-varying and periodic nature of the model dynamics, a simple online power estimator is used to track the load dynamics in real time. The control system is composed of a tracking controller and dynamic grid disturbance rejection controller, with contribution of the DER and CIL under existence of diode bridge loads. In this case, the controllable DER, not only provides some part of active power to the non-linear load, it also tries to alleviate harmonic problems in the source current. The harmonic compensation and PQ improvement is implemented in a multi-converter system with contribution of controllable DER and CIL as a constant power load (CPL). The PQ improvement in this paper is respect to the harmonic compensation and other issues regarding power quality are not considered. The harmonic rejection is tested while CPL is operation as active filter and it is compared to the active filtering performance of DER unit. A detailed simulations of a low-voltage microgrid system performed in PSCAD/EMTDC verify that the controllable DER can be successfully applied for harmonic compensation as well as acting as an active power source.

MICROGRID

The structure of the microgrid system under study is shown in Fig. 1. This model consists of one controllable DER unit connected to the AC feeder at the point of common coupling (PCC). Another converter works in rectifier mode as CIL. The distribution system consists of a non-linear load connecting to the AC grid. The microgrid can be disconnected from the main grid in the utility interruption or any event. Controllable unit includes an energy source, and a grid-interfacing VSC which is controlled in PWM adjusted by the current control scheme. The microgrid can operate in grid-connected or islanding mode.

In grid-connected operation, the microgrid is connected to the utility, and the DER unit provides the local loads as well as power support for the whole grid. Once transferred to islanding operation, the DER must immediately provide the changed power demand and continue supplying power to all critical and non-critical loads within the microgrid [7]. The *LC* filter is used for voltage disturbances of each unit and the series inductance also represents the leakage inductance of the coupling transformer.

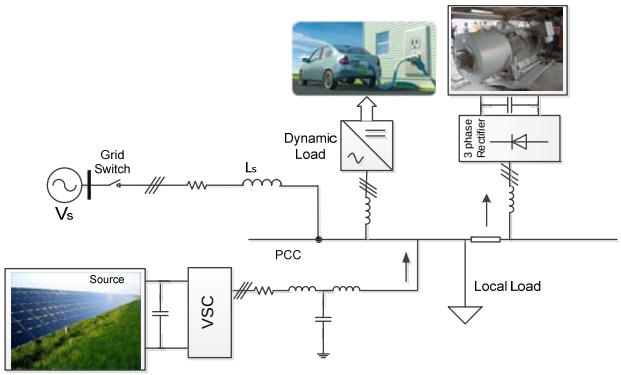

Fig. 1. Single line diagram of microgrid system with renewable resources

The designed microgrid system operates in autonomous mode as well as grid-connected. In result of an event in the utility system, the grid switch at PCC opens and the microgrid is disconnected from the utility and provides all the loads operating in autonomous converter mode. A seamless transition to the autonomous mode is provided by the frequency synchronization technique which is adjusted based on the data given from the frequency characteristics of the microgrid.

CONTROL SYSTEM

Schematic of the controller for multi-converter system implemented in SRF is indicated in Fig. 2. All of the equations and calculations for the control and compensation are in the two axis frame translating by the Clarke transform of the line current and phase voltages. The control method is based on decoupling independent control of I_d and I_q in a rotating SRF. Also a frequency control loop is added to the controller for frequency stabilization [8].

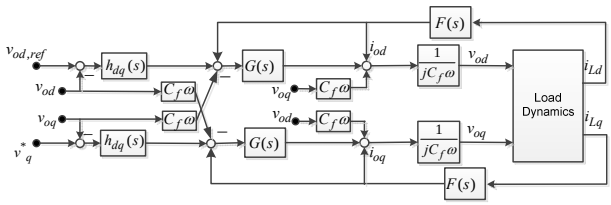

Fig. 2. Block diagram of the controller for multi-unit system in SRF.

Current components of compensator are added to the reference generator as a cascade controller. The decoupling control model is designed based on the dynamic equations of the system in SRF. The control system consists of three blocks such as current controller, voltage controller and frequency controller.

Harmonic Detection and Compensation

The harmonic compensation is done based on the reference currents produced from the instantaneous reactive power (IRP) block and added to the current control. In this paper a fast method for harmonic detection is used based on the instantaneous pq theory [6]. The method is resulted from the dividing the current in four components representing oscillating and fundamental part of the active and non-active power [2]:

$$i_{\alpha,\tilde{p}} = \frac{v_\alpha}{v_\alpha^2 + v_\beta^2}(-\tilde{p}) \quad i_{\alpha,q} = \frac{v_\beta}{v_\alpha^2 + v_\beta^2}(-q)$$
$$i_{\beta,\tilde{p}} = \frac{v_\beta}{v_\alpha^2 + v_\beta^2}(-\tilde{p}) \quad i_{\beta,q} = \frac{-v_a}{v_\alpha^2 + v_\beta^2}(-q) \qquad (1)$$

Pq Theory using low pass filter

The control strategy for the pq theory with low pass filter is based on the calculation of the oscillating components of the instantaneous power [6]. The average active power consumed by the load is assumed to be constant means the load is time invariant. The pq method for compensating the harmonic power is depicted in Fig. 3. The instantaneous active and non-active power definition is as follows:

$$p = v_\alpha i_\alpha + v_\beta i_\beta$$
$$q = v_\beta i_\alpha - v_\alpha i_\beta \qquad (2)$$

Where, the voltages and currents in two axis stationary frame are resulted from Clarke transformation. Then active and non-active currents are obtained from:

$$\begin{bmatrix} i_{\alpha,ref} \\ i_{\beta,ref} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p^* \\ q^* \end{bmatrix} \qquad (3)$$

Where $p^* = -\tilde{p} + \bar{p}_{loss}$, $q^* = -q$ and the reference currents are in $\alpha\beta$ frame. After determining current components, they are transformed into the rotating frame that is synchronized with the grid by the angle θ. In this method, d and q represent active and reactive components of load respectively.

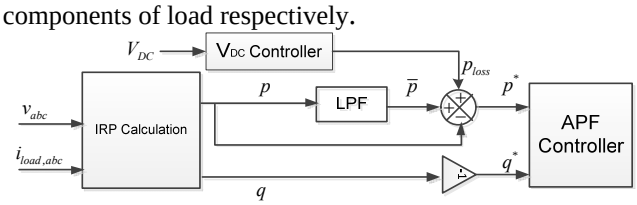

Fig. 3. Control block for the instantaneous power theory

CASE STUDY AND SIMULATION RESULTS

The microgrid system under study supplies a nonlinear load that is a diode bridge rectifier with a load of 15 kVA. The uncontrolled rectifier injects harmonics in order $n = 2pk \pm 1,\ k = 1,2,\ldots$, where p is number of branches in the rectifier [1]. So, for this case with a three branch uncontrolled the harmonics in order of 5, 7, 11, 13,… are injected to the grid. The amplitudes decrease by the order of harmonic as follows [9].

$$I_n = \frac{I_1}{\left(\frac{n-5}{n}\right)^{1.2}}$$

The total harmonic distortion (THD) is used for the evaluation of power quality and distortion of the waveforms for current and voltage. The harmonies are categorized as even harmonics, multiples of three and not multiples of three [10]. The harmonic limits for not multiples of three are higher than multiples of three. The limitation for the current harmonics also depends on the short circuit ratio (SCR) and the types of the equipment's [11].

The simulation is done in two distinct cases first in the islanded mode with active filtering performance of the DER and second in islanded mode while CIL operates as active filter. In the first study when the DER unit provides active filtering it is observed that the THD of the source current depends on the power supplied by the DER and in higher power supply the more distorted source current is resulted. It is because of the sinusoidal current that is supplied by the DER to the grid. This current increases the distortion of the source current which is depicted in Fig. 4 using KCL at the PCC.

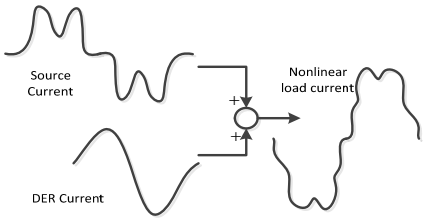

Fig. 4. KCL at the PCC

Compensation By The DER Unit

In this case, the VSC supplies 5 kW in the rating of the DER and remaining is provided by the grid source. The THD for load current is equal to 22%. The DER unit is operating as active filter using the reference signals from the IRP calculation. In the active filtering mode, the THD of the source current drops fall from 22% to 3% that is a significant improvement. In power generating mode, the power quality improvement is provided simultaneously with providing active power. In this case, three modes are investigated such as active filtering mode, power generation mode supplying rated power and power generation with 10 kW active power supply. The inverter is supplying the reference currents calculated by the IRP.

In purely active filtering mode the THD of the source current decreases to 3%, but it increases to 5% in power generation. This becomes worse while the converter operates also as DER with the increased power. In the rating operation, the THD of the source current is still acceptable in a wide range of operation [11], [12].

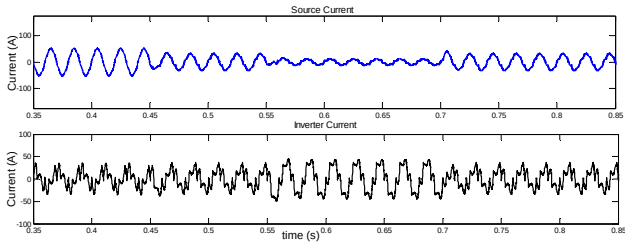

Fig. 5. Source current and the inverter current upon the power variation

Fig. 5 shows the current waveforms for the supplied current by the inverter, in comparison to the grid current. The inverter in the instant t=0.45 s, goes from active filtering to the power generating mode and in this state, delivers power in rating of the DER (5 kW). At t=0.55 s, the power available from the inverter is increased and at t=0.7 s, the power is reduced again stepwise.

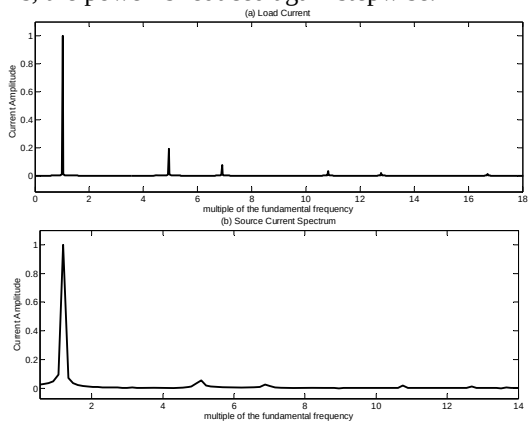

Fig. 6. Spectrum of the load current and the source current

The dynamic performance of the controller and harmonic compensator is tested by switching between three operation modes. Inverter provides the load power demand locally such as active, reactive and harmonics. It results to maintain the grid side currents sinusoidal at unity power factor. Regarding the %THD limits for distributed systems, IEC [11] and IEEE [12] Standards impose a limit of 5% on the current produced by the DER and the load, while in both active filtering and active power modes, the THD limits are respected.

When the power supplied by the DER is increased the THD is increased to more than 10% which is out of limits. The spectrum of the load current and compensated source current in active power mode are shown in Fig. 6.The significant mitigation of all of the harmonics is seen in the figure. It shows the sufficient performance of the active filter designed in this paper. The magnitudes of the harmonics are not comparable with the fundamental component. The window for THD calculation in PSCAD/EMTDC is designed to detect harmonics up to

harmonic order of 15th.

Active filtering performance of the CPL

In the second case study, the grid is disconnected and CPL provides active filtering based on the *p-q* method similar to the previous case. The THD of the source current is reduced from 22% to 2% once operating in active filtering mode. It means that the lower frequency current harmonics having higher magnitudes are effectively compensated. At time t=0.55s, CPL starts consuming active power from the grid. The THD of the source current is further reduced to 1.5%. This is because of the addition of sinusoidal current drawn by the CPL to the source current as mentioned before. The THD variations during three modes of operation are presented in the Fig. 7.

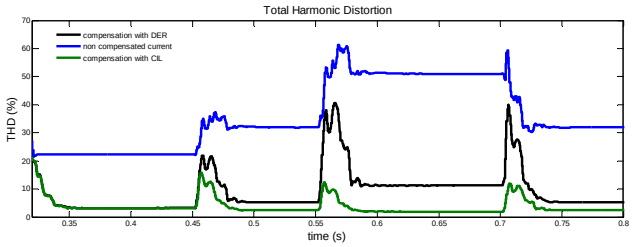

Fig. 7. Current distortion for different compensation strategies

The blue curve in the Fig. 7 is related the source current without compensation while black line indicates THD of the grid current in the grid-connected mode and operation of DER as the active filter. The green curve indicated THD of the inverter current upon CPL operation as active filter in three modes of pure active filtering, absorbing power of 5kW and loading in 10 kW. As shown in the plot, the performance of the DER and CPL are similar in the pure active filtering mode, while CPL provides higher harmonic compensation in the active power mode with active filtering as an ancillary service. The THD of the source current in different active filtering Scenarios without DER and grid connected mode with and without current control is listed in Table 1.

Table 1: THD assessment in different cases

Scenario	Current THD (%)
Disconnected DER	22
Grid-connected mode with 10 kW active power	10.2
Grid-connected mode with 5 kW active power	5.3
Active filtering mode	3.25
Compensation with CPL	2

CONCLUSIONS

This paper has investigated the capability of controllable DERs and CILs in a microgrid as shunt active power filters. The power quality in different operation modes of the microgrid has been significantly improved respected to the operation of DER. The controller successfully manages any variation in active power feeding into the grid and simultaneously the inverter can be effectively utilized for power conditioning without affecting its normal operation of power generation. Inverter with the proposed approach eliminates the need for additional power conditioning equipment with operating as a shunt APF. Current compensation by CPL reduces the THD to the minimum value. It has been observed that the natural operation of CPL and DER also contributes in the reduction or exaggeration of current THD by absorbing or adding a sinusoidal term in the grid. In this case, the interfacing inverter, providing active filtering features in smart grid, eliminates the device cost for power conditioning devices which is more than 100 $/kVA in low voltage level [13]. Since the THD is not sufficient measure of the current harmonics, the frequency spectrum is added to verify the performance of the method in different harmonics.

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