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Design and Implementation of a DSP based High-Performance DG Inverter

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Abstract: This paper presents a DSP based high-performance power flow control scheme for the distributed generation (DG) inverter. The design of control scheme is based on a detailed dynamic model of the 3-phase voltage sourced inverter. In the dynamic model, the DG energy source is represented by a constant DC voltage. To achieve better dynamic performance, the output power flow of the inverter is controlled through a P-Q decoupled control algorithm based on two independent regulation loops for d-q currents. The proposed control scheme with various DG operating conditions is firstly simulated in the PSIM software environment to check the performance of the designed controllers and followed by a set of DSP based experimental tests. The results obtained have demonstrated the feasibility and effectiveness of the proposed control scheme in providing a desirable dynamic performance of fast real and reactive power regulations of the grid-connected DG inverter.

Keywords: Distributed Generation, Voltage Sourced Inverter, P-Q Control Scheme, Digital Signal Processor

Nomenclature

DG	distributed generation
VSI	voltage source inverter
$PWM1-6$	pulse width modulation signals for the 6 IGBTs
PCC	point of common coupling
V_{an}, V_{bn}, V_{cn}	line to neutral voltages of the grid
I_{Sa}, I_{Sb}, I_{Sc}	3-phase line currents on the grid side
I_{La}, I_{Lb}, I_{Lc}	3-phase line currents of the local load
$I_{Capa}, I_{Capb}, I_{Capc}$	3-phase line currents of the output capacitors
L, C	inductor and capacitor of the output LP filter
I_{Oa}, I_{Ob}, I_{Oc}	the 3-phase inductor currents
V_{dc}	the dc voltage of the DG inverter
V_{An}, V_{Bn}, V_{Cn}	the voltage across each leg (A, B and C) to the neutral
V_{tm}	voltage of the PWM carrier
V_{cona}	the phase-a control signal
V_{conb}	the phase-b control signal
V_{conc}	the phase-c control signal
V_{cond}, V_{conq}	the equivalent d-q control signals
I_{Sd}, I_{Sq}	the equivalent d-q currents on the grid side
I_{Od}, I_{Oq}	the equivalent d-q inductor currents
I_{Ld}, I_{Lq}	the equivalent d-q load currents
P_{DG}	the output real power of the DG inverter
Q_{DG}	the output reactive power of the DG inverter
I_{DGd}	the d-axis current command of the DG inverter
I_{DGq}	the q-axis current command of the DG inverter
V_d, V_q	the d-q axis grid voltages

1 Introduction

To reduce the adverse effects of using fossil fuel on the environment and response to the progressive shortage of conventional energy resources, e.g. oil, natural gas and coal [1,2], the fast development of renewable energies,

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distributed generations (DG) [3,4] and micro-grids (MG) [5,6,7,8] is an inevitable trend. However, due to the increased number of grid-connected DG and the vast application of nonlinear power converters and electronic devices the complexity of securely operating the power distribution systems has been greatly increased. Therefore, seeking for feasible measures to ensure a high standard electric power system and to develop new and flexible power flow control interfaces for the DG systems is an urgent need. Distributed generations (DGs) are normally small-scale electricity generations and considered as a solution for addressing new concepts in technical, economical and environmental issues of conventional power systems. In recent years, the application of DGs is under extensive studies and experimental tests. It is recognized that these systems create a number of technical challenges concerning the operation, monitoring, control and protection of new DG embedded systems. Theoretically, the DG systems with various renewable energy resources can be connected to the network in series- or shunt-type power interface. The shunt-type connection injects current at the point of common coupling (PCC) as shown in Fig. 1, while the series-type connection injects a voltage between the utility supply and the customer load as shown in Fig. 2. It is quite obvious that the control complexities and efforts for the series-type connection are much higher than that for the shunt-type connection. Because the controlled real power and possible compensated quantities, e.g. reactive power or harmonics are directly related to the regulation of currents in nature, shunt-type connection is more realistic as it is originally designed to inject currents at the PCC. In this paper, the shunt-type voltage source inverter (VSI) for interfacing between the DG working in a MG and the connected distribution network is investigated. A systematic way to consider the emerging potential of DG is to take a system approach, which views generation and associated loads and controllers as a MG [9,10]. In general, a micro-grid can operate as a grid-connected system or as an islanded system. However, utilities may not allow the islanding operation of micro-grids unless the island does not include any part of the utility system. For a micro-grid operated in grid-connected modes, one of the major technical concerns is its dynamic power flow control capability. This paper presents a DSP based flexible P-Q control scheme for the DG inverter working in a typical micro-grid with local loads. By making use of the proposed multi-loop, d-q current control scheme, the inherent interferences between real and reactive power can be effectively suppressed. The design of the proposed control scheme is based on a detailed dynamic network model considering the overall system operating conditions. The proposed new control scheme is so designed that it controls the inverter, which interfaces the DC energy source to the grid, in an independent current-control mode. In this paper, the overall test system is firstly described and simulated in the PSIM software environment followed by a set of DSP based experimental tests to verify the overall performance of the proposed control scheme. Typical results are then presented with brief discussions.

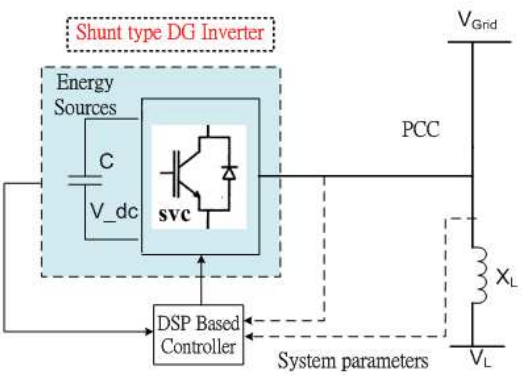

Fig. 1: The shunt-type power interface of a DG

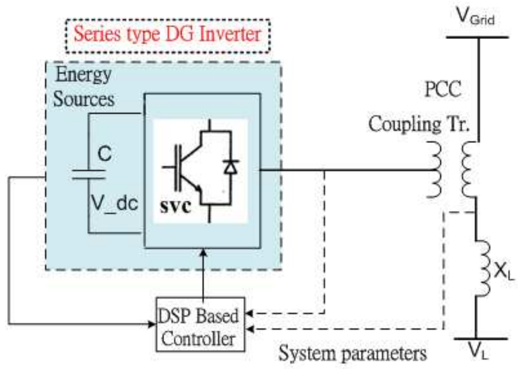

Fig. 2: The series-type power interface of a DG

2 System Modeling and Design of P-Q Decoupled Controllers

The current controlled Voltage Source Inverter (VSI) is normally used for interfacing between shunt-type DG and distribution networks. In this paper, the command signals for the DG inverter will include the information of active power supplied from DG system and reactive power required to compensate the reactive power demanded by the load or to eliminate the voltage fluctuation on load-side buses. The load harmonic currents can also be compensated with the proposed current control structure if so desired. As mentioned previously, to allow performing fast P-Q control functions, current controlled VSI is utilized in this paper for its fast dynamic response and ease of implementation to guarantee the required

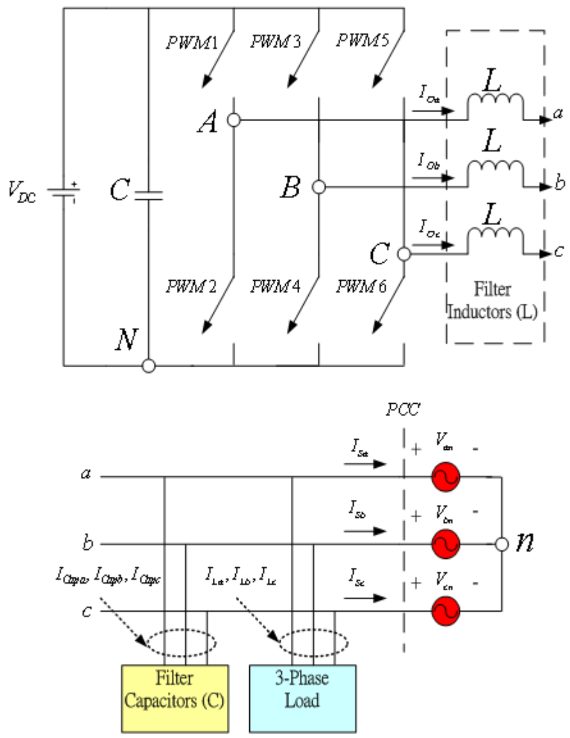

Fig. 3: The detailed DG system circuit

dynamic performance. The d-q axis current control techniques of VSI proposed in this paper is based on analysis of voltage and current vector components in a special reference frame. In this paper, the synchronization algorithm uses the instantaneous angle of load voltage calculated directly by decomposing voltage vector components in a rotating reference frame. Using this control strategy, synchronization problems will be resolved and dynamic response of DG can be significantly improved. As mentioned previously, the main objective of the proposed control technique is to achieve fast real power regulation, load reactive power compensation and to track rapid variations in load harmonic currents if the function is activated. Based on the detailed DG system circuit shown in Fig. 3, the relationships among voltage and current parameters can be expressed as follows:

$$L\frac{dI_{Oa}}{dt} = V_{AN} - V_{an} - V_{nN} \quad (1)$$

$$L\frac{dI_{Ob}}{dt} = V_{BN} - V_{bn} - V_{nN} \quad (2)$$

$$L\frac{dI_{Oc}}{dt} = V_{CN} - V_{cn} - V_{nN} \quad (3)$$

For a balanced 3-phase system, the following mathematical expressions (4)-(8) can be easily derived.

$$V_{nN} = \frac{(V_{AN}+V_{BN}+V_{CN}) - (V_{an}+V_{bn}+V_{cn})}{3} \quad (4)$$

$$\begin{bmatrix} L\frac{dI_{Oa}}{dt} \\ L\frac{dI_{Ob}}{dt} \\ L\frac{dI_{Oc}}{dt} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ \frac{-1}{2} & 1 & \frac{-1}{2} \\ \frac{-1}{2} & \frac{-1}{2} & 1 \end{bmatrix} \left(\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} - \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \right) \quad (5)$$

$$I_{Capa} = C\frac{dV_{an}}{dt} = I_{Oa} - I_{La} - I_{sa} \quad (6)$$

$$I_{Capb} = C\frac{dV_{bn}}{dt} = I_{Ob} - I_{Lb} - I_{sb} \quad (7)$$

$$I_{Capc} = C\frac{dV_{cn}}{dt} = I_{Oc} - I_{Lc} - I_{sc} \quad (8)$$

Using the defined switching functions, given in (9), for the three-phase inverter, the decoupled system model can be obtained with some mathematical manipulations as expressed in (10)-(11).

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \frac{V_{dc}}{2}\begin{bmatrix} 1+\frac{V_{cona}}{V_{tm}} & 1+\frac{V_{conb}}{V_{tm}} & 1+\frac{V_{conc}}{V_{tm}} \end{bmatrix}^T \quad (9)$$

$$\begin{bmatrix} L\frac{dI_{Oq}}{dt} \\ L\frac{dI_{Od}}{dt} \end{bmatrix} = \frac{V_{dc}}{2V_{tm}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} I_{Capq} \\ I_{Capd} \end{bmatrix} = \begin{bmatrix} C\frac{dV_q}{dt} \\ C\frac{dV_d}{dt} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} I_{Oq} \\ I_{Od} \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} I_{Lq} \\ I_{Ld} \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} I_{Sq} \\ I_{Sd} \end{bmatrix} \quad (11)$$

Based on the decoupled model derived in (11), the current commands for the desired DG real and reactive power flow can be directly obtained as follows.

$$\begin{bmatrix} P_{DG} \\ Q_{DG} \end{bmatrix} = \begin{bmatrix} V_q I_{DGq} + V dI_{DGd} \\ V_q I_{DGd} - V dI_{DGq} \end{bmatrix} \quad (12)$$

It can be proved that when the inverter output voltages are in synchronous with the grid voltages, the d-axis voltage component becomes zero. This leads to the following results.

$$\begin{bmatrix} P_{DG} \\ Q_{DG} \end{bmatrix} = \begin{bmatrix} V_q I_{DGq} \\ V_q I_{DGd} \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} I^*_{OP} \\ I^*_{OQ} \end{bmatrix} = \begin{bmatrix} I^*_{DGq} \\ I^*_{DGd} \end{bmatrix} = \begin{bmatrix} P_{DG}/Vq \\ Q_{DG}/Vq \end{bmatrix} \quad (14)$$

With the derived current commands expressed in (14), the overall control structure of the DG and the designed parameters for PI controllers are respectively shown in Fig. 4 and 5. As can be seen in Fig. 4, the proposed control scheme is designed with a dual-loop structure using high-gain inner-loop current controllers and functional P-Q outer-loop controllers. In this type of grid connected inverter system, high band-width currentcontrol loop must be used. In this paper, the controllers are implemented in d-q synchronously rotating reference frame using 4 properly designed PI controllers as shown in Fig. 5.

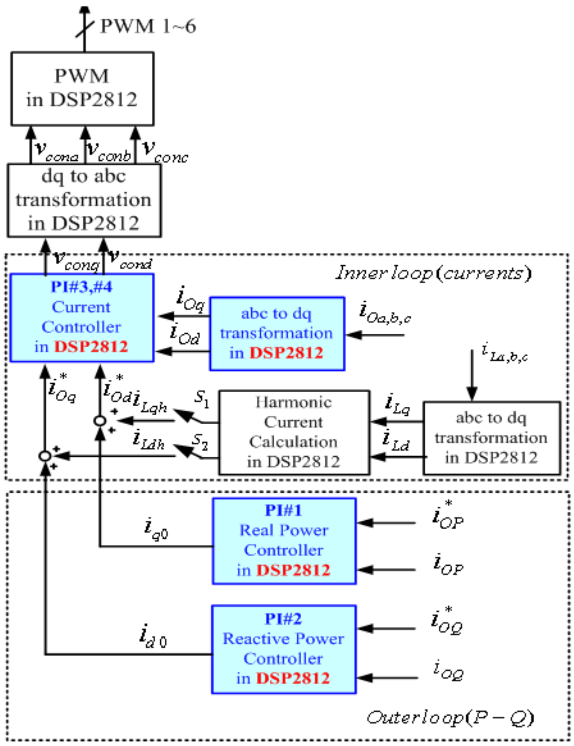

Fig. 4: The overall control structure

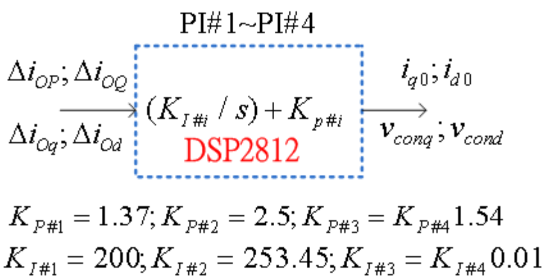

Fig. 5: The designed parameters for PI controllers

3 Simulation and Experimental Tests

The related data concerning the DG inverter system and the arrangement of local load are given below.

– System Capacity of the DG: 5kVA
– Grid Voltage: 220V(L-L)/60Hz
– Inverter Parameters: Switching frequency: 24kHz, Filter (1.5 mH, 4.7uF), V_{dc} = 400V, C = 1000uF.
– Load: The local loads are disconnected (in grid-tie operation).
– Control Functions: In this paper, only reactive power tracking functions are discussed.

As addressed previously, besides the quantitative design of real and reavtive power flow controllers with comprehansive numerical simulation studies, the overall performance of the proposed control scheme is experimentally tested as configured in Fig. 6. In the hardware setup, a digital controller based three phase grid-connected DG inverter and a set of voltage and current sensors are used. Test conditions and system parameters are given at the beginning of this section. All the required controllers proposed in this paper are implemented with TI DSP2812. The sensed currents and voltages acquired to the DSP and the control signals output to the driving circuits are using home-made signal acquisition circuits. Both of the sampling frequency and the switching frequency are set at 24 kHz. Fig. 7 to 10 show the first set of comparative simulation and experimental results regarding the simulation and practically measured reactive power, voltages and currents of the studied grid-connected DG inverter. The control commands for the DG inverter are set as follows: The output real power is set to zero throughout the simulation period. During the simulation time from 0.4 to 0.5 seconds, the output reactive power is set to 1.3kVar and zero Var for the time period between 0.5 and 0.6 seconds. A negative 1.3kVar command is issued for the time period from 0.6 to 0.7 seconds. In the experimental tests, the operation of reactive power commands is set exactly the same as that used in simulation studies. Fig. 11 to 18 show a set of the detailed results regarding the dynamic reactive power flow tracking performance with two step-up and two step-down in control command. In both the simulation and experimental tests, it is found that the interference between the output real and reactive power of the DG inverter can be perfectly eliminated with the proposed DSP based dual-loop current control scheme.

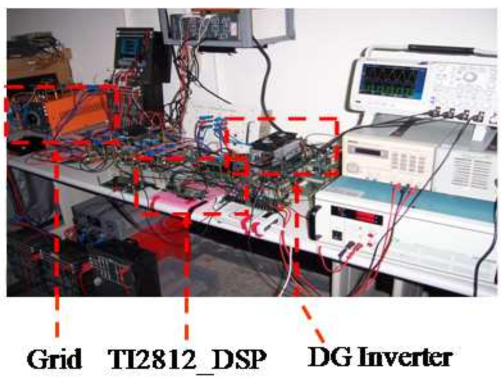

Fig. 6: The experimental setup of the DSP based DG inverter system

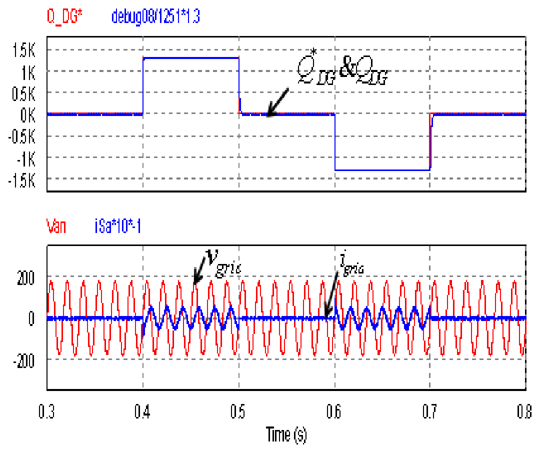

Fig. 7: The reactive power tracking results with voltage and current waveforms (simulation)

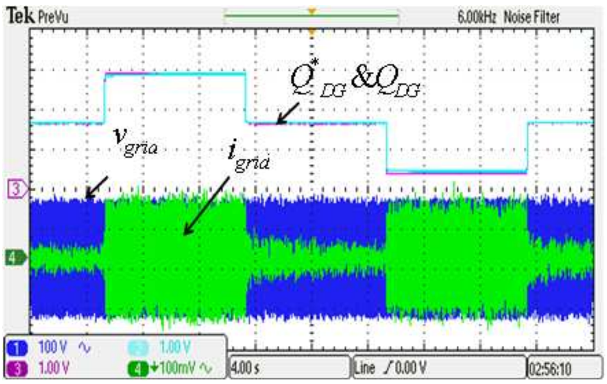

Fig. 8: The reactive power tracking results with voltage and current waveforms (measured); Time (4s/div), Q (1kW/div; 1kVar/div)

4 Conclusion

This paper has presented a DSP based high-performance control scheme for the DG inverter to perform fast real and reactive power flow control functions. It is important to note that the proposed dual-loop, direct d-q current control scheme has fast dynamic response in tracking real and reactive current commands since the control loops of active and reactive power are considered independent. Using the proposed control method, a DG inverter system can be considered as a new alternative for performing functions of distributed static synchronous generator (DSSG) in distribution networks or a active power filter if so desired. Both experimental and simulation results indicate that the proposed DG inverter system is able to provide multiple power flow control functions in all system operating conditions. Based on the measured

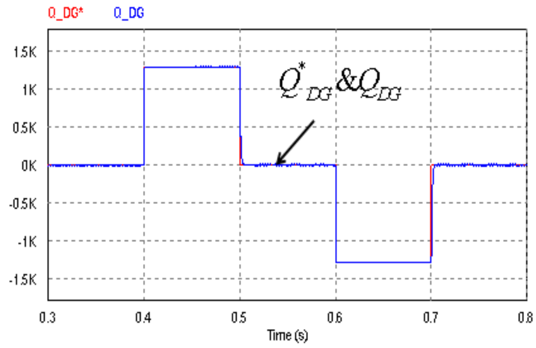

Fig. 9: The detailed reactive power tracking results (simulation)

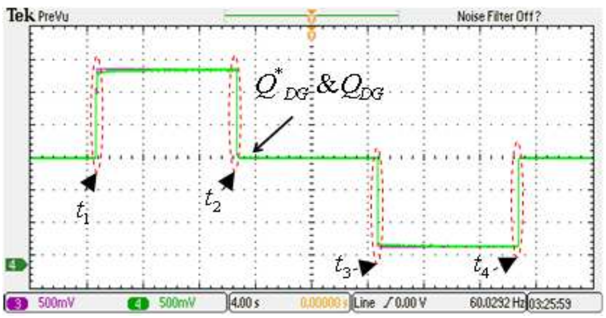

Fig. 10: The detailed reactive power tracking results (measured); Time (4s/div), Q (500Var/div)

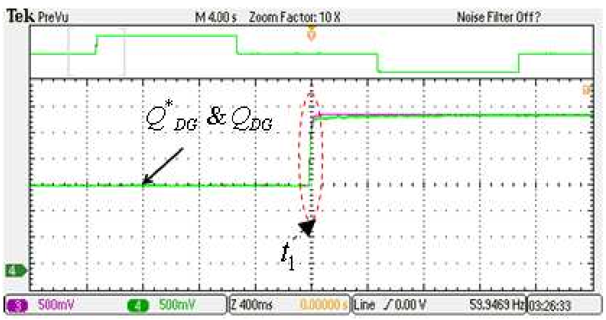

Fig. 11: The dynamic response of reactive power tracking results at t_1 (measured); Time (4s/div), Q (500Var/div)

results obtained from the DSP based hardware tests, the feasibility and effectiveness of the proposed control scheme have been fully verified.

Acknowledgement

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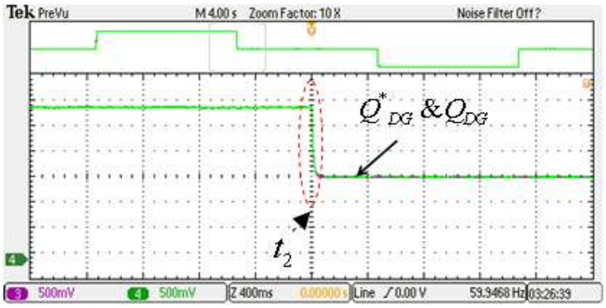

Fig. 12: The dynamic response of reactive power tracking results at t_2 (measured); Time (4s/div), Q (500Var/div)

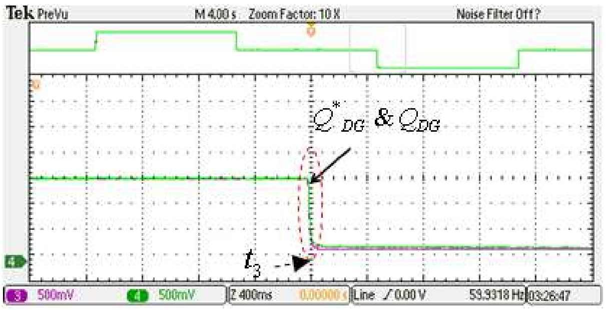

Fig. 13: The dynamic response of reactive power tracking results at t_3 (measured); Time (4s/div), Q (500Var/div)

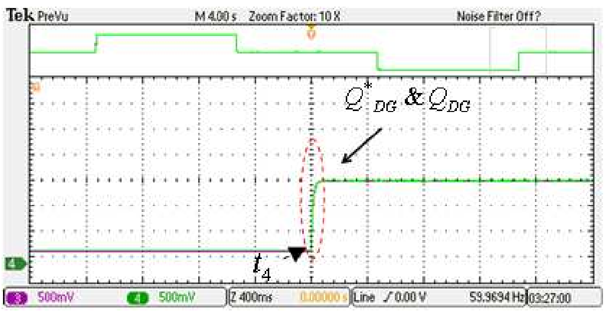

Fig. 14: The dynamic response of reactive power tracking results at t_4 (measured); Time (4s/div), Q (500Var/div)

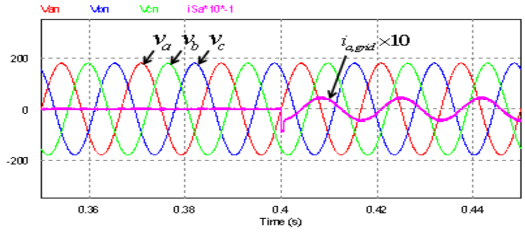

Fig. 15: The voltage and current waveforms at step-up instant of t_1 (simulation)

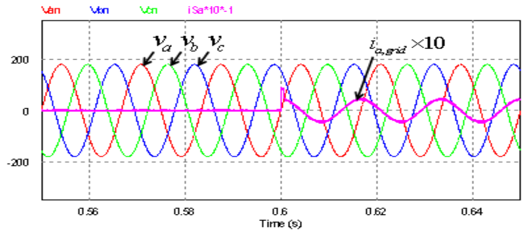

Fig. 16: The voltage and current waveforms at step-down instant t_3 (simulation)

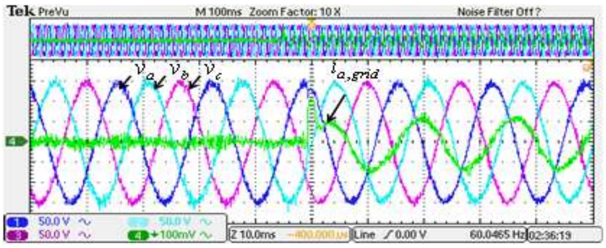

Fig. 17: The voltage and current waveforms at step-up instant of t_1 (measured)

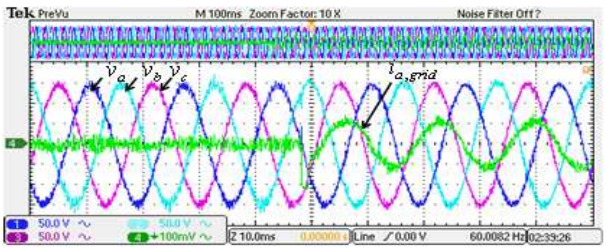

Fig. 18: The voltage and current waveforms at step-down instant t_3 (measured)

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