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Robust State Feedback Controller for Photovoltaic Inverter System using Unbundled Smart Meter

Navonita Sharma, Ajoy Kumar Chakraborty

Abstract**:** ***The paper proposes the integration of photovoltaics into distribution power system through inverter control and optimally managing the power flow based on smart energy meter data. The concept of Unbundled Smart Meter (USM) is used which to optimally integrate the inverter control logic with in the Smart meter which requires the construction of SMX (Smart Meter Extension) library. The proposed approach is adapted to make the design more robust and dynamic. State feedback controller has been designed to control the power flow to and from between the inverter and grid through USM and hence provide additional services to support grid operations. The proposed system gives the flexibility of adding numerous functionalities in the installed smart meter without the fuss of firmware change and hence integration of renewables to grid becomes more efficient as the meter's instantaneous data are used in the dynamic control of the system. The validation of the proposed scheme is achieved by time domain simulations on MATLAB/Simulink R2018a platform along with Arduino programming on Proteus 8.1 software. These results are further assessed through Hardware experiment observations.***

Keywords: State Feedback Control, Unbundled Smart Meter, Grid Connected Inverter, Ancillary services.

I. INTRODUCTION

With large scale integration of renewable to grid, the importance of dynamic and robust control of the incoming and outgoing power from renewable energy sources to grid and vice versa has grown many folds. Role of fast and reliable control of grid connected inverters is very significant in today's scenario when the world is moving towards 100% renewable generation. Many literatures of past and present suggested the use of modern tools and techniques to implement better control of grid connected inverters. The benefits of feedback control have been known since long. The formal development of feedback as a mathematical tool for analysis of the behavior of dynamical systems has begun around 150 years ago when Maxwell published his work on governors [1]. Since then State Feedback (SFB) control has been widely used in many control applications including the control of grid connected inverters. Though there have been many advancements in control logic over the years, SFB control still possess the popularity among many recent technical literatures for control of grid connected inverter. D. Lalili et. al [2], in their paper proposed the state Feedback Linearization Control technique for the control of power factor of a three-level photovoltaic inverter connected to grid. The control scheme deploys transformation of nonlinear state models of inverter into d-q reference frame to create separate subsystems to control constant dc link voltage and power factor of the grid. State feedback controllers are also used for controlling the states of voltage source inverter with LCL filters [3] and LC filters [4]. State feedback control offers full controllability, which enhances the stability and increases damping to reduce filter resonances. Baochao Wang et. al [5] proposes the extended state observer concept (ESO) which unlike the conventional observer can robustly handle the observer dynamics and parameter variation of the system model. Similar approach for designing of current estimator has been proposed by Roner A. Liston Jr et. al [6], where a new estimator for the current filter capacitor is presented for its operation with a filter resonance frequency of wide range. They have also showed active damping of current filters using the estimator and proposes proportional resonant (PR) controller with harmonic compensation (HC) to control the inverters connected to grid. More recent advancement in state feedback controllers are also depicted in many literatures, such as Seung-Jin Yoon [7], where integral SFB controller have been proposed to effectively control the grid-tied three-phase inverter dynamics. The discrete-time integrator incorporated in the state feedback controller ensures both the reference tracking and disturbance rejection performance of the inverter system in a practical and simple way. Similarly, Ricardo Perez-Ibacache et. al [8], proposed in their work a state feedback primary control strategy for microgrids with multiple distributed energy resources. Each distributed energy resources are model as a nonlinear dynamic system which are then controlled using nonlinear full SFB controller. All these advancements in controller design are not made considering instantaneous grid requirement. As more and more renewables are getting induced in the grid, the status of grid voltage and power requirements changes rapidly more than ever. In present scenarios, the need of dynamic control based on instantaneous grid signals is the need of current decentralized power system which is rapidly moving towards 100 percent renewable power generations. Such rapid control of power flow to and from the grid is possible when instantaneous grid requirements is known and this is made possible with the help of smart meters.

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But integrating inverter control with smart meter is not feasible with existing smart meter architecture. Unbundled Smart Meters provide the solution to this problem. The concept of unbundled smart meter (USM) was first developed by Nobel Grid's project, Horizon 2020, in April 2015. The unbundled smart meter (USM) can be seen as an architectural systematization in which smart meter functionalities are clubbed in two separate (unbundled) parts, making the ensemble both metrology proof and highly flexible. Out of the two parts one is dedicated for metrological and hard real time functions, and is known as the smart metrology meter (SMM). It is designed to have fixed (freeze) functionality and high security of recorded data (black boxlike standard). The other part is called smart meter extension (SMX) which is designed to support high flexibility needed for new functionalities that need to be installed in the meter during the meter's lifespan. It also supports the future evolution of the smart grid and energy services. The use of USMs in various smart grid operations has been depicted in different literature studies, most of which is carried out by H2020 project. Mihai Sanduleac et.al are the main contributors of the study in USM. Sanduleac. M et.al [9] in their paper presented the use of USM in smart cities where multiple ownership results in the need for multiple access to meter data. They showed that for developing smart cities the smart meter data needs to be accessed securely by all active actors like energy suppliers, consumers and utilities simultaneously, which is not possible through old architecture of smart meters. Similarly, Dorel Stanescu et.al [10] in this article showed the testing and validation of USM architecture for smart city development. Mihaela M et al. in their papers [11] and [12] proposed power quality (PQ) monitoring and control using voltage parameter assessment feature implemented in USM. Mihai Sanduleac et al. in their researches [13], [14], [15] addressed the LV network observability and control issues and proposes the solution of USM architecture. Mihai Sanduleac et al. [16] also presented an approach in his research article for integrating Electrical Vehicles in the Smart Grid with the application of unbundled Smart Metering. M. Monfared et.al [17], in their presented work proposed a digital dead-beat power control technique for single phase inverters connected to grid. Similarly, application of decoupled power control has been proposed by Xiaofeng Sun et.al [18], where they have used an adaptive droop control method for the control of an inverter connected distributed generator connected in distribution system using online evaluation of power decouple matrix. Zhilei Yao et.al [19], proposed an improved control strategy for control of three-phase grid connected inverter. In their presented work, they have used the reference grid current, in the decoupled components of the grid current controller to be replaced by controlled grid current. Unbundled Smart Meters are the new trend in smart metering design and application. With the flexibility of adding additional functionality, USM can provide power inverter management [20]. Similar case study has been presented here where the control of PV inverter is based on the instantaneous data obtained from the USM. This integration can facilitate power curtailments and ancillary services as PV inverters can provide both production and storage facilities. In this work, authors present the concept of using USM data for dynamic real time control of inverters integrating renewables to grid. USM data is used to analyze real time grid conditions and hence generates the instantaneous control signals as per grid power demands. The SMX (Smart Meter Extension) functionality of USM allows the integration of control logic of inverter with the meter, thereby making the control robust and real time fast. The concept of optimized penetration of renewable to grid via control of 3 phase grid connected inverters has been presented here. The control strategy adapted here is State Feedback control. The organization of this paper is as follows. Section 2 describes the step by step methodology and Section 3 describes the state space modeling of three-phase inverter system linked to grid through DC link capacitor. Section 4 present the state feedback controller design technique Section 5 describes the use of unbundled smart meter data in control- ling the inverter along with the integration of inverter with meter. Section 6 shows the simulation result and analysis of the control logic along with supported experiment results. Section 7 presents the conclusion. All the simulation and analysis are carried out in MATLAB/ SIMULINK R2018a and Proteus environment.

II. METHODOLOGY

1. All three phase quantities such as voltage and current are measured using unbundled smart meter (USM) and then is converted into synchronously rotating d-q quantities using Park's transform.
2. The equations of grid connected inverter system with L filter is developed in state space and the corresponding system matrices are generated
3. The control of d-q axis quantities has been done using State feedback controller for given reference values generated by the USM.
4. Pole placement method has been used to determine the gains of the State Feedback Controller
5. Feed forward terms are used to decouple the control signals, so that active and reactive power can be controlled independently.
6. The controlled d-q axis quantities and converted back to three phase quantities by Inverse Park's transform.
7. The controlled three phase signal generates the PWM signals for the gate drive of inverter circuit.

III. STATE SPACE REPRESENTATION OF GRID CONNECTED INVERTER

Since the state feedback control is a model- based approach, the precise system model and the discretization process are the most important factors for efficient design of the controller. All three- phase variables are transformed into the synchronous reference frame using the following equations in order to obtain the system model in the synchronous reference frame, the three-phase voltages are represented by these following equations:

$$V_a = \sqrt{2}V_s\cos\omega t \tag{1}$$

$$V_b = \sqrt{2}V_s\cos(\omega t - 120^0) \tag{2}$$

$$V_c = \sqrt{2}V_s\cos(\omega t - 240^0) \tag{3}$$

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The transformation from three-phase to dq reference frame is made in two steps:

- A transformation from the three-phase coordinate system to the two-phase ab/α β, stationary coordinate system governing by Equations.:

$$V_\alpha = \tfrac{3}{2} V_a = \tfrac{3}{2}\sqrt{2} V_s \cos\omega t \qquad (4)$$

$$V_\beta = \tfrac{\sqrt{3}}{2}(V_b - V_c) = \tfrac{\sqrt{3}}{2}\sqrt{2} V_s \sin\omega t \qquad (5)$$

- A transformation from the ab/ coordinate system to the rotating coordinate system:

$$V_d = (V_\alpha \cos\theta + V_\beta \sin\theta) \qquad (6)$$

$$V_q = (-V_\alpha \sin\theta + V_\beta \cos\theta) \qquad (7)$$
$$where, \theta = \angle(V_d - V_\alpha)$$

Figure 1 shows a three-phase grid connected inverter, where Vpv denotes the DC-Link voltage R and L are the filter resistances and filter inductances, respectively.

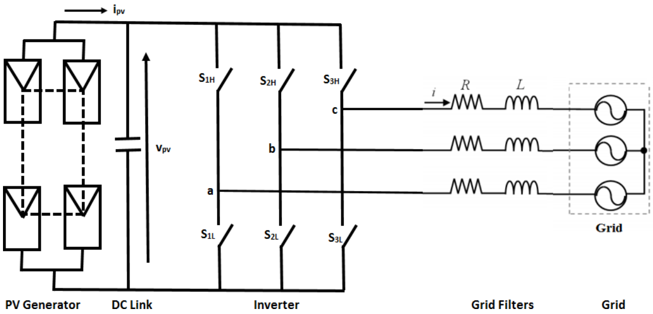

Figure 1 Schematic of Grid connected Inverter

From figure 1, the system can be mathematically expressed in synchronous reference frame as:

$$Ri_d + L\frac{di_d}{dt} - \omega L i_q + V_{id} = 0$$
$$\frac{di_d}{dt} = \frac{(0 - V_{id})}{L} - \frac{R}{L} i_d + \omega i_q \qquad (8)$$

$$Ri_q + L\frac{di_q}{dt} + \omega L i_d + V_{iq} = V_{sq}$$
$$\frac{di_q}{dt} = \frac{(V_{sq} - V_{iq})}{L} - \frac{R}{L} i_q - \omega i_d \qquad (9)$$

Where,

$$0 - V_{id} = V_{id}'' \qquad (10)$$

$$V_{sq} - V_{iq} = V_{iq}'' \qquad (11)$$

From Equation (8), (9), (10) and (11) the state space model of the inverter can be obtained as

$$x' = Ax + Bu \qquad (12)$$

$$y = Cx \qquad (13)$$

Where x' = [i_d i_q] is the system state vector, and u = [V''_{id} V''_{iq}], is system input vector. The system A, B and C matrices can be expressed as:

$$A = \begin{bmatrix} -\frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \; and\; C = [1 \quad 1]$$

The converter is modeled using its gain G and the inverter time Td. The delay Td is equal to half the time period of the carrier signal. And the Inverter Gain G is defined as:

$$G = \frac{V_{dc}}{2V_c} \qquad (14)$$

Where Vdc is DC link voltage and VC is the peak of the triangular carrier used in PWM. The inverter can be mathematically represented as:

$$\frac{G}{1 + sT_d}$$

To eliminate the cross coupling that exist between the d-q terms, feed forward terms are added with the controlled output as shown in the following equations:

$$V_d^* = -V_{id}'' + V_{dff} = -V_{id}'' + \frac{\omega L_{iq}}{G} \qquad (15)$$

$$V_q^* = -V_{iq}'' + V_{qff} = -V_{iq}'' + \left(\frac{V_{sq}}{G} - \frac{\omega L_{id}}{G}\right) \qquad (16)$$

IV. STATE FEEDBACK CONTROLLER DESIGN

The State space design method is based on pole placement method in which all closed loop poles are placed at desired locations with the quadratic optimal regulator method. The system parameters considered for the case study in this paper is as follows:

Table 1 Specification of System Parameters

Sl. No.	Parameters	Value
1.	AC Side Voltage	35 V
2.	Filter Inductance	3 mH
3.	DC Voltage	70 V
4.	Converter Gain (G)	35
5.	Carrier Frequency of Sine PWM Generator (Fsw)	5 KHz
6.	Filter Resistance	0.5 Ω

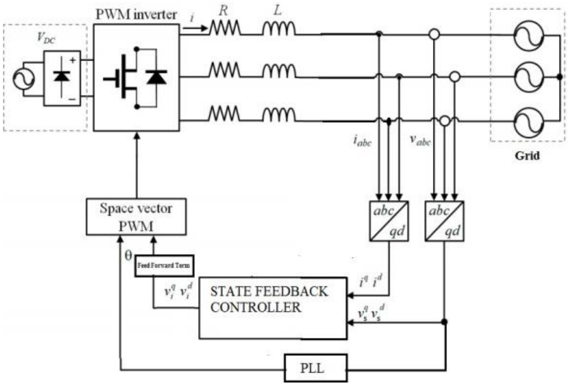

Figure 2 Schematic of control scheme

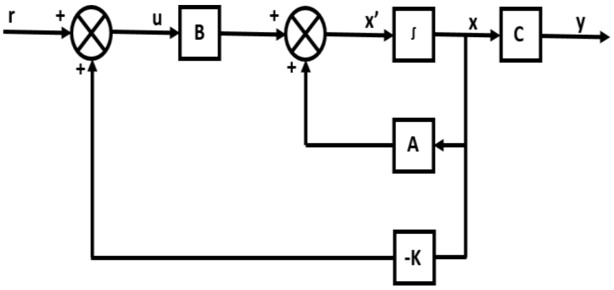

Figure 3 Block diagram of State Feedback Control System [21]

Assume a plant not represented in phase-variable form [21]

$$z' = Az + Bu \tag{17}$$

$$y = Cz \tag{18}$$

whose controllability matrix is:

$$C_{Mz} = [B \quad AB \quad A^2B \ldots \quad A^{n-1}B] \tag{19}$$

Assume that the system can be transformed into the phase-variable (x) representation with the transformation

$$z = Px \tag{20}$$

Substituting this transformation into Equation (17) we get

$$x' = P^{-1}APx + P^{-1}Bu \tag{21}$$

$$Y = CPx \tag{22}$$

Whose controllability matrix is

$$C_{Mx} = P^{-1}[B \quad AB \quad A^2B \ldots \quad A^{n-1}B] \tag{23}$$

Substituting Equation (19) into Equation (23) and solving for P we obtain:

$$P = C_{Mz}C_{Mx}^{-1} \tag{24}$$

Thus, the transformation matrix, P, can be found from the two controllability matrices. After transforming the system to phase variables, we design the feedback gains. Hence, including both feedback and input, $u = -k_x x + r$, Eqn (21) and (22) becomes

$$x' = P^{-1}APx + P^{-1}BK_xx + P^{-1}Br \tag{25}$$

$$Y = CPx \tag{26}$$

Since this equation is in phase-variable form, the zeros of this closed-loop system are determined from the polynomial formed from the elements of C_P. Using $x = P^{-1}z$, we transform Eqs. (12) and (13) from phase variables back to the original representation and get,

$$z' = Az - BK_xP^{-1}z + Br = (A - BK_xP^{-1})z + Br \tag{27}$$

$$Y = Cz \tag{28}$$

Comparing Eqs. (17) with

$$\begin{aligned} x' = Ax + Bu &= Ax + B(-Kx + r) \\ &= (A - BK)x + Br \end{aligned}$$

The state variable feedback gains, K_z, for the original system is:

$$K_z = K_xP^{-1} \tag{29}$$

Hence, the controller gains are obtained. For the given system design the controller gains are calculated are $K_1 = -0.4976$, $K_2 = 0.9433$, $K_3 = -0.9433$ and $K_4 = -0.4976$.

V. UNBUNDLED SMART METER

Traditional smart meters usually have one embedded architecture for the metrology and other functionalities. Hence, they do not possess the flexibility of adding new features as per the local requirement of meter setup. Because to add a new function, complete up gradation of the existing firmware is required. This implies that the meter needs a new metrology certification which is both unreasonable and expensive. In the current paradigm the evolution of new functions needs to occur at a faster rate for proper management and control of smart grid. Unbundled Smart Meters as the name suggest are separated or unbundled into two separated parts unlike the integrated Smart Meters. This development makes the meter much more flexible for users and as well as developers. Since the programmable part (Smart Meter Extension i.e. SMX) is now separated from the fixed part (Smart Metrology Meter i.e. SMM), the reprogramming and data access of the meter has been made much easier. How USM can contribute towards inverter integration to grid has been briefly explained by Vasco Delgad- Gomes et.al [20]. They addressed that existing smart meters are not prepared for an emergency energy market since they do not provide the flexibility of data access, nor they can be reprogrammed to be integrated with LV/MV distribution network.

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Based on their observation and proposed architecture, this paper presents the USM approach for controlling grid connected inverter using communication channel to provide instantaneous grid requirement and hence generating the required control reference signals. The USM acts as a residential gateway, enabling the control of three-phase inverter using an IP-based secure communication network.

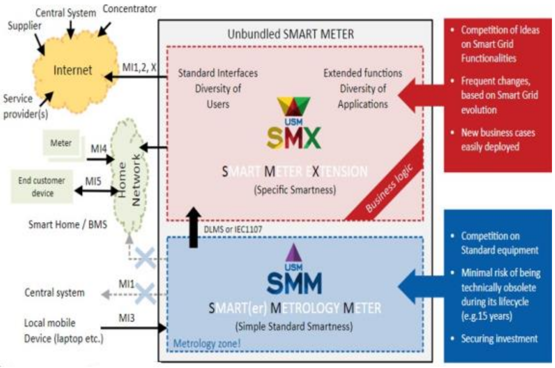

Figure 4 Architecture of Unbundled Smart Meter [20]

To generate real time data a model of smart meter has been designed in Proteus simulation platform and the energy monitoring feature has been added to the microcontroller. The following figure 5 shows the schematic of Arduino UNO programmed as SMX to monitor grid condition. The above model is then connected to MATLAB Simulink using Simulink support packages of MATLAB. In the Simulink, inverter and grid models are then connected to Proteus's Arduino UNO smart meter to generate the reference signals. Serial communication has been established between MATLAB and Proteus using Simulink Support Package for Arduino Hardware and Arduino IDE programming.

VI. SIMULATIONS AND EXPERIMENT RESULTS

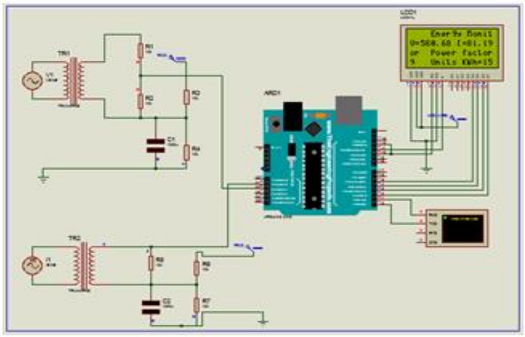

Figure 5 Arduino UNO schematic used for energy monitoring

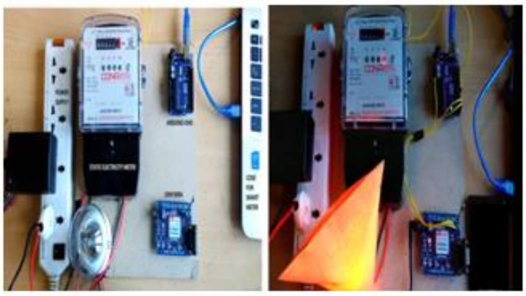

Figure 6 Practical Model of Smart Meter

Arduino UNO is generally programmed with codes written in Arduino IDE but it can also be programmed using MAT-LAB Simulink package for Arduino. Simulink blocks are used to read analog signals from the meter and PWM pins are used to output signals to control inverter as per requirement.

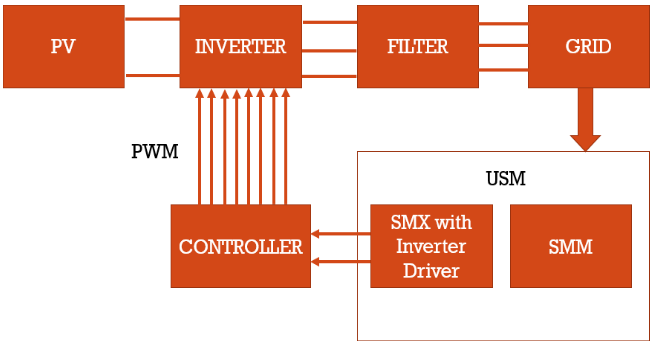

Figure 7 Schematic of USM based inverter control

Instantaneous power requirement of the grid can be recorded and sent to the inverter control board, through the communication link. Based on the data, control signals for Id and Iq has been generated and thus the control is provided for rapid grid change scenarios. The reference signals are generated from grids power requirement, using the following equations:

$$P = \frac{2}{3} V_{sq} i_q \qquad (30)$$

$$Q = \frac{2}{3} V_{sq} i_d \qquad (31)$$

From the given specification and applying d-q transformation on AC side voltage, we obtain a $V_{sq} = 52.5$ V. The simulations were performed for a large range of data set generated from designed smart meter. These case studies show the versatility of the proposed controller. Each case study presents a unique scenario of power demands exhibit by the grid, and how the proposed controller can robustly control the active and reactive power independently. The results obtained through simulation of the proposed scheme is as follows:

Table 2 Simulation Results for Observed I_d and I_q

Power Requirement of Grid		References generated based on Grid Requirement		Observed		Error	
Reactive (Q) (VAR)	**Active (P) (WATT)**	**I_d (A)**	**I_q (A)**	**I_d (A)**	**I_q (A)**	**I_d (A)**	**I_q (A)**
0	175	0	5	-0.000015	5	0.000015	0
105	245	3	7	3	7	0	0
-210	315	-6	9	-6.001	9	0.001	0
140	280	4	8	4.003	8	0.003	0
-105	0	-3	0	-2.99	0.0006	0.01	0.0006

Table 3 Simulation Results for Observed Active and Reactive Power

Power Requirement of Grid		Observed		Error	
Reactive (Q) (VAR)	**Active (P) (WATT)**	**Q (VAR)**	**P (WATT)**	**Q (VAR)**	**P (WATT)**
0	175	-0.00052	175	0.00052	0
105	245	105	245	0	0
-210	315	-210	315	0	0
140	280	140.1	280	0	0
-105	0	-105	0.021	0	0.021

The simulation and experiment graphs for some selected above-mentioned case studies are as follows:

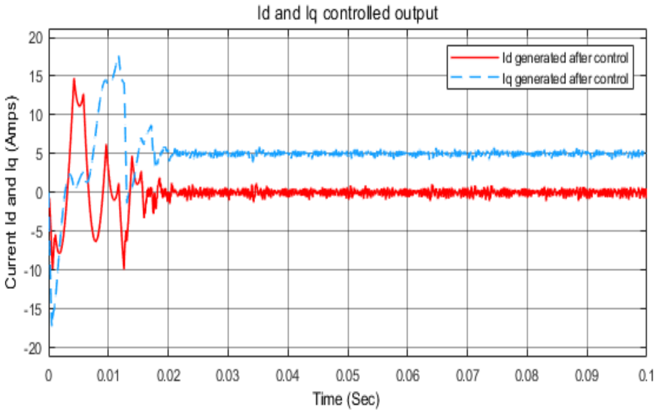

Figure 8 CASE 1: SIMULATION RESULTS: Observed Value for Id and Iq Reference value of Id = 0 A and Iq = 5 A

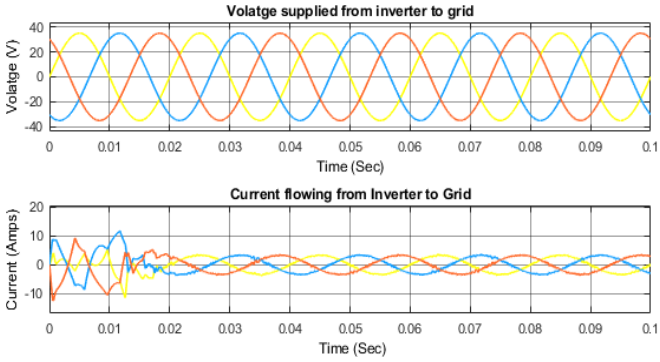

Figure 9 CASE 1: SIMULATION RESULTS: Voltage and Current flowing from inverter to grid for the given Id and Iq

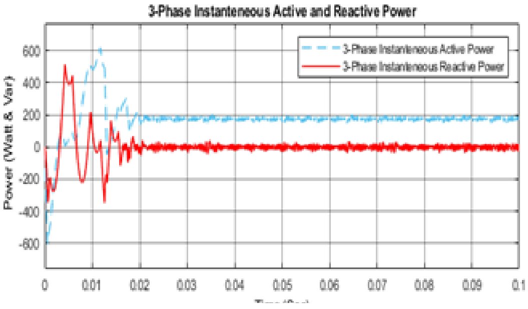

Figure 10 CASE 1: SIMULATION RESULTS: 3 Phase Instantaneous Active and Reactive Power Corresponding Id and Iq

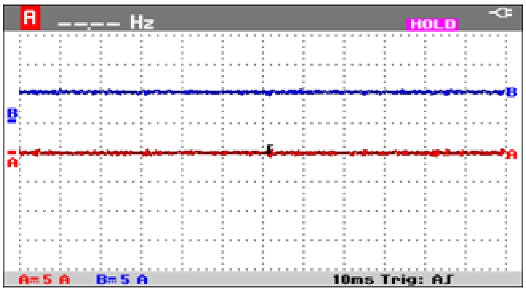

Figure 11 CASE 1: HARDWARE EXPERIMENT RESULTS: Scope results to show the Id and Iq output from real time system for given reference values of Id = 0 A and Iq = 5 A (Scope A represent Id and Scope B represent Iq)

CASE 1: Analysis: The above case study represents the situation when the grid requirement for reactive power is zero and only active power needs to be transmitted to grid. Both the hardware and simulation results show the efficiency of the controller to control the active power independently while limiting the reactive power to zero.

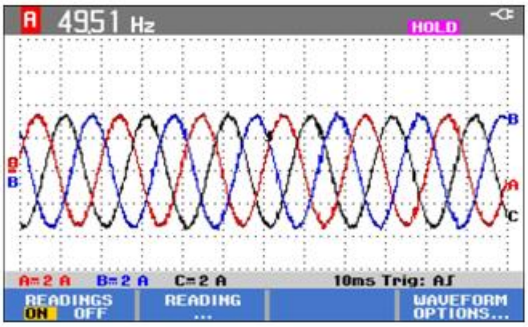

Figure 12 CASE 1: HARDWARE EXPERIMENT RESULTS: Scope results showing current flowing from inverter to grid for the given Id and Iq

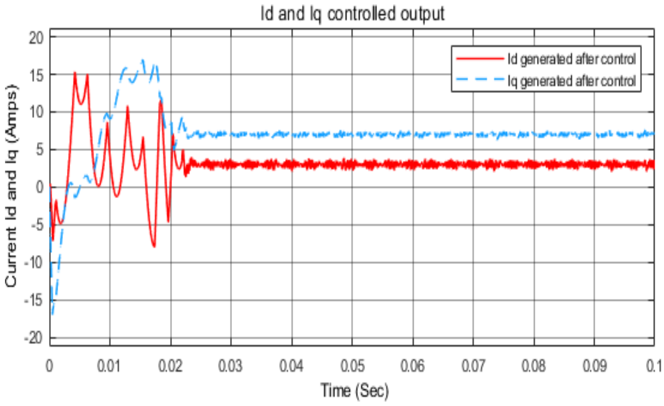

Figure 13 CASE 2: SIMULATION RESULTS: Observed Value for Id and Iq Reference value of Id = 3 A and Iq = 7 A

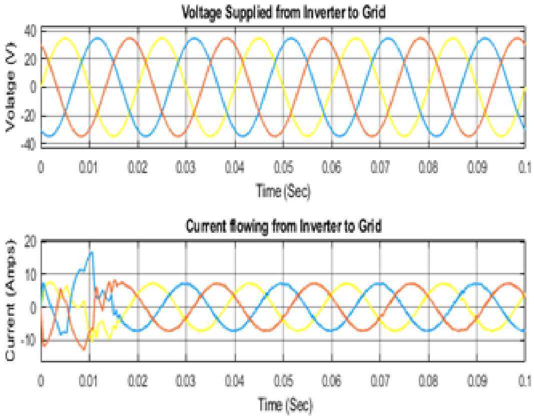

Figure 14 CASE 2: SIMULATION RESULTS: Voltage and Current flowing from inverter to grid for the given Id and Iq

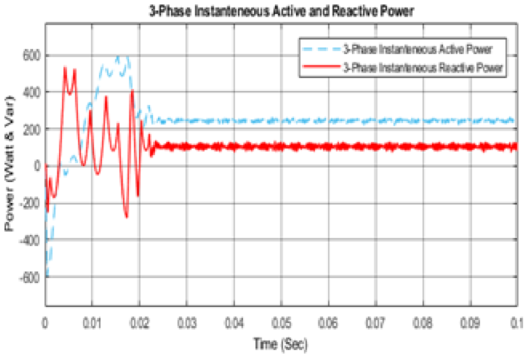

Figure 15 CASE 2: SIMULATION RESULTS: 3 Phase Instantaneous Active and Reactive Power Corresponding Id and Iq

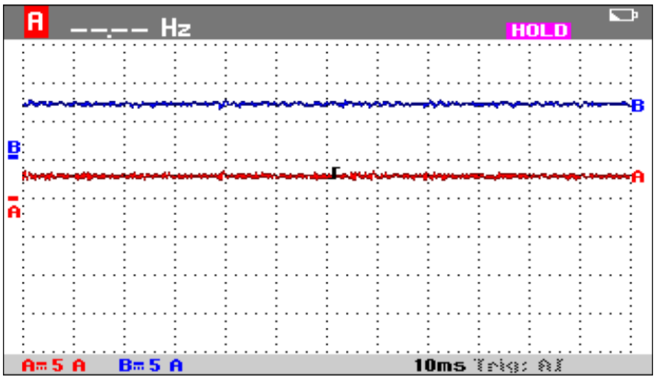

Figure 16 CASE 2: HARDWARE EXPERIMENT RESULTS: Scope results to show the I_d and I_q output from real time systemfor given refenrence values of I_d= 3A and I_q= 7A (Scope A represents I_d and Scope B represents I_q)

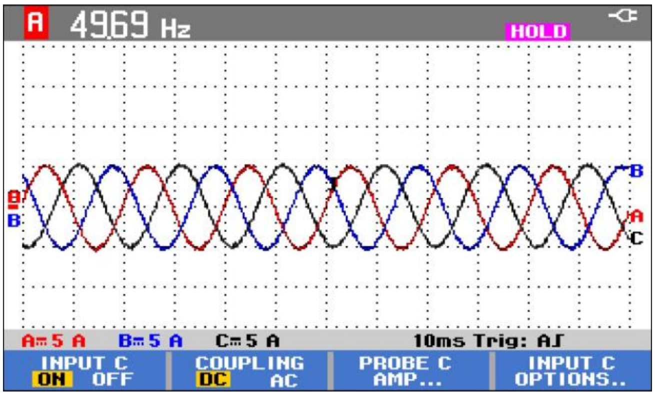

Figure 17 CASE 2: HARDWARE EXPERIMENT RESULTS: Scope results showing current flowing from inverter to grid for the given I_d and I_q

CASE 2: Analysis: This case study shows the scenario when both active and reactive powers are required by the grid and hence generates a positive current (I_d and I_q) reference for inverter. The simulations and experiment conducted show the output of the inverter same as the reference with minimum error. The designed controller can feed both active and reactive power independently to the grid.

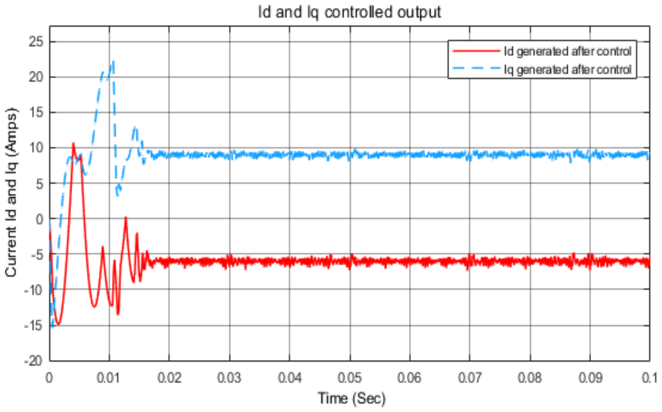

Figure 18 CASE 3: SIMULATION RESULTS: Observed Value for Id and Iq Reference value of Id = -6 A and Iq = 9 A

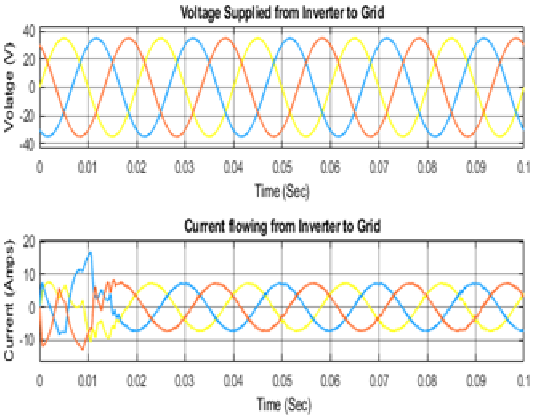

Figure 19 CASE 3: SIMULATION RESULTS: Voltage and Current flowing from inverter to grid for the given Id and Iq

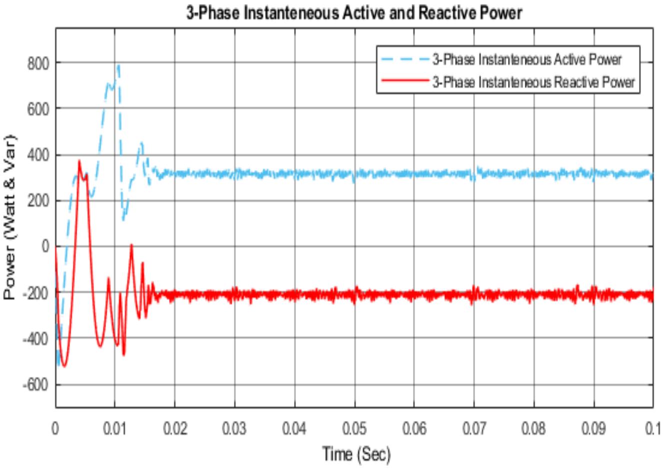

Figure 20 CASE 3: SIMULATION RESULTS: 3 Phase Instantaneous Active and Reactive Power Corresponding Id and Iq

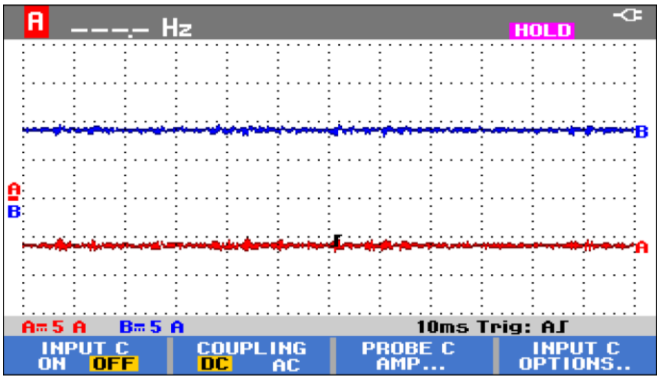

Figure 21 CASE 3: HARDWARE EXPERIMENT RESULTS: Scope results to show the I_d and I_q output from real time system for given reference values of I_d= -6A and I_q= 9A (Scope A represents I_d and scope B represents I_q)

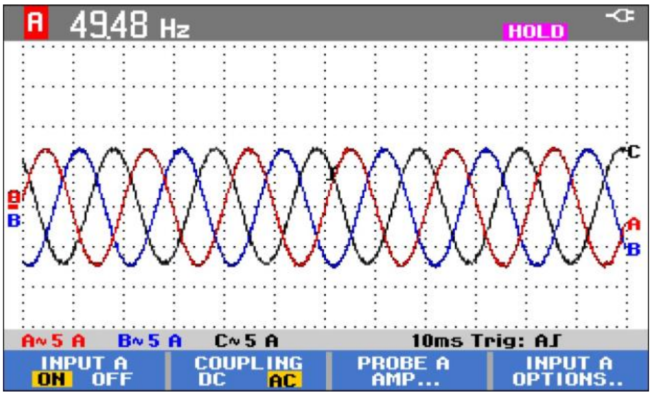

Figure 22 CASE 3: HARDWARE EXPERIMENT RESULTS: Scope results showing current flowing from inverter to grid for the given I_d and I_q

CASE 3: Analysis: This case study represents the situation when the grid requires active power but at the same time needs to dump the excess reactive power in the system to maintain voltage balance. This issue is resolved by setting the Id reference to a negative value so that reactive power from the grid could flow back to the inverter system and hence maintains the reactive power balance in the grid.

Hence, the controller can also provide ancillary services to the grid. All the above case studies depict 3 scenarios, when the grid requirement changes instantly and dynamically. To make the power flow efficient, optimal and to help the grid maintain a balance, instant accessibility to the grid requirement is crucial. Smart meter data obtained from the SCADA server of utility is used here to provide the instant references. The overshoot in the dynamic responses as shown in the simulation results is because the controller takes one cycle of input signal to generate the required feedback to stabilize the plant. The dynamic overshoot does not lasts more than 0.02 seconds i.e. the 1st cycle of the input signal.

Table 4 Observed Hardware Experiment Results for I_d and I_q

Power Requirement of Grid		References generated based on Grid Requirement		Observed		Error	
Reactive (Q) (VAR)	Active (P) (WATT)	I_d (A)	I_q (A)	I_d (A)	I_q (A)	I_d (A)	I_q (A)
0	175	0	5	0.1	4.97	0.1	0.03
105	245	3	7	2.88	7.06	0.12	0.06
-210	315	-6	9	-6.02	8.97	0.02	0.03

VII. CONCLUSIONS

In this proposed study a robust State Feedback Controller has been designed to control the PV inverter according to grid requirement and thus promotes the optimized penetration of renewables to the grid. The main purpose of using the USM is that it gives the flexibility of adding new features to the meter without changing its original firmware and hence in this proposed approach the control of the inverter is integrated with the meter's recorded data of instantaneous grid conditions which makes the control more dynamic and robust. Data from USM is fed to the controller through communication channels, and this data are used to generate the control signals. The independent curtailments and production of both active and reactive power are shown for the proposed scheme. During grid abnormality, the control system is recognized to inject reactive power to support the grid operation. The control scheme is found to be robust against environmental variations and also proves to be efficient in providing proper ancillary services for grid operations. Flexibility of the said scheme is that the inverter services and control logic are not implemented in the SMX driver, rather the control has been developed through communication channels with the USM. The control operates as per commands of SMX library which is different for different inverters. This makes the model versatile enough to be used for various inverter ratings.

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