Dynamic analysis for grid tied PV inverter under controlled environment

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Photovoltaic (PV) inverter is the basic unit for low voltage ride through (LVRT) to determine dynamics of grid tied PV plant. There are various control methods for PV inverter. In this paper two methods i.e. Taguchi and Ziegler-Nicholas are used to tune and control the proportional–integral (PI) controller for PV inverter. Based on the study of modeling and simulation by PSCAD/EMTDC, it was analyzed and proved that feasibility and effectiveness of grid tied PV model under controlled environment. For this purpose a detail model grid tied PV model is designed in PSCAD. Cascaded control scheme is used for grid-tied PV inverter. Cascade controller using PI controllers are fine-tuned using Taguchi Approach and Ziegler-Nicholas method. Simulation results indicate the capability of the PV system to ride through the faults determined by low voltage ride through (LVRT) under Taguchi tuning method is better than Ziegler-Nicholas Method.

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Keywords: Photovoltaic, LVRT, grid Integration, Taguchi approach, Ziegler-Nicholas, PSCAD, MPPT

1. Introduction

Power generation from renewable energy resources and its interconnection with power grid is one of the major concerns. Conversion of solar energy through PV system has now reached to advanced phase. As a green energy source it can now contribute to the overall conservation of the environment. Development in the power semi-conductor technology has made possible the clean and efficient conversion of solar energy into electrical energy through a PV cell. A PV module generally is a source of low power DC that cannot be directly interconnected to the grid applications. A power converter is required that converts the raw electrical power generated by solar PV module into the usable electrical power. The output power of the solar PV module is variable for a fixed input condition of solar cell temperature and solar radiation level. In addition, the output power extracted from the solar PV module is a function of current and voltage. There is a set of these variables at a particular temperature and load at which the power drawn from the solar PV module is maximum. Maximum power point tracker (MPPT) is required which can continuously extract the maximum power out of the PV module. A converter is used that not only converts the raw electrical power into usable electrical power but can also extract maximum power. Once power is extracted then it is regulated as per defined inverter topology for AC voltage. In order to get perfect AC voltage fine tuning of PI controllers is required. For this purpose Taguchi Approach [1] is chosen. With the increased penetration of solar PV system into the distributed generation, study of the dynamic model of PV module and its applicability is one of the important aspect of the PV system.

The Ziegler–Nichols tuning method is a heuristic method of tuning a PI controller. It is performed by setting the integral (K_i) and derivative (K_d) gains to zero. The proportional gain, K_p is then increased (from zero) until it reaches the ultimate gain K_u, at which the output of the control loop oscillates with a constant amplitude. K_u and the oscillation period T_u are used to set the P, I, and D gains depending on the type of controller used. But this method fails to work well when the processes are high-order and nonlinear [11].

The PSCAD/EMTDC is a simulation tool [2] used for the integration of distributed power generation resources such as PV that can accurately model both the fast power system dynamics and slow power generation dynamics of solar PV module. However PSCAD simulation package lacks the valid simulation model. Extensive study of grid interface of PV system requires accurate PV model in PSCAD/EMTDC.

In this paper first a complete simulation model is developed for grid connected PV in the PSCAD/EMTDC software that accurately models the PV characteristics including the effect of temperature as well as solar radiation level. Further a MPPT controller is also used for the DC-DC converter using incremental conductance tracking algorithm for the PV model. Tuning of PI is given main focus and Taguchi approach is used to evaluate the invertor output voltage under various symmetrical fault conditions. The grid side voltage after the fine tuning of the PI controller using Taguchi approach are presented in simulation results. This will help us in easy and efficient control in interconnection under fault.

2. PV Array Simulation

Modeling of solar cell using an electrical equivalent circuit is as shown in Fig. 1. The DC current *Isc* produced varies linearly with solar irradiance. The current *Id* through the diode is largely responsible for producing the nonlinear *I-V* characteristics of the PV cell shown in Fig. **2**. The PV cell model can be further refined by including a second diode that provides even more accurate *I-V* [3].

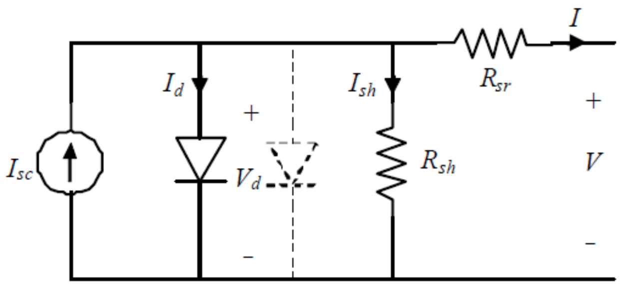

Fig 1. PV Cell equivalent circuit.

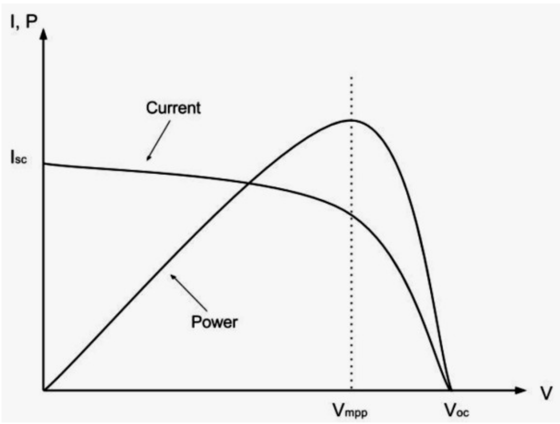

Fig 2. Typical I-V characteristics.

3. Maximum power point tracking

Maximum power that can be drawn by a solar cell depends on the operating point on the *I-V* curve and the maximum power output occurs around the knee point shown in Fig.2 of the curve. By using an intelligent MPPT algorithm, it ensures the PV module always operates at its maximum power point irrespective of the variation in temperature, solar radiation and the load. A number of tracking algorithms have been proven and used. In this model incremental conductance algorithm is used. Further, a number of DC-DC converter topologies are possible to control the system/invertor voltage [4,5]. The open circuit voltage and the maximum power point voltage are sensitive to the cell temperature. At higher temperatures the efficiency of solar cells drops. These temperature dependencies are included in the PV cell model as it requires cell temperature as an input shown in Fig. 3.

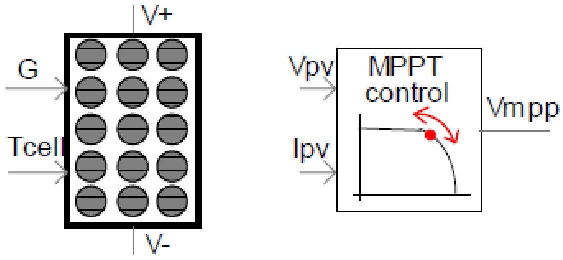

Fig 3. PV system simulation components library developed for PSCAD.

4. Grid connected PV system

A block diagram for grid connected PV system is shown in Fig. 4 whereas Fig 5 illustrates the simulation model for grid connected PV model developed in PSCAD. For the simplicity of presentation, the grid system is represented only as an equivalent source behind the system impedance. The inverter is connected to the 11 kV grid through a step-up transformer.

By using a large DC link capacitor, the PV source current ripples are minimized. DC-DC converter is used for MPPT by controlling the voltage across the DC link capacitor and the PV array. This is achieved by first creating a reference voltage that is supplied to a PI controller which creates switching signals that force the voltage across the PV array to follow the reference voltage which further refers to following two stages.

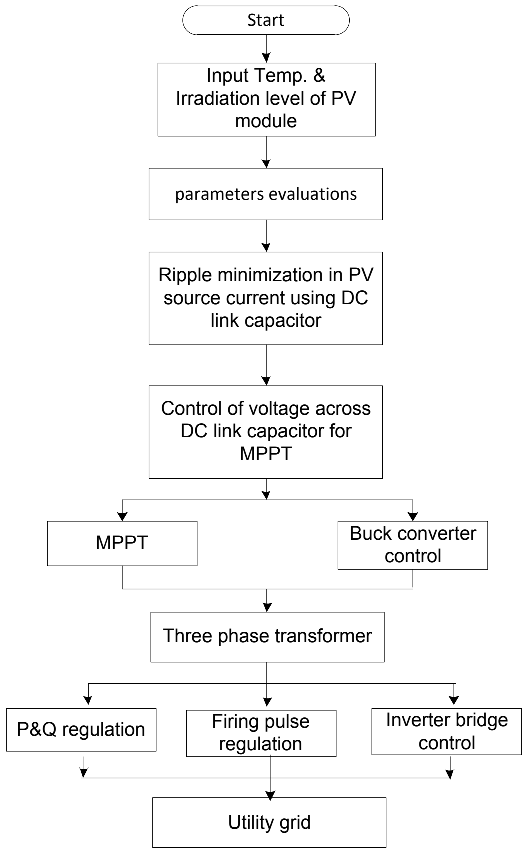

Fig 4. Block diagram for grid connected PV system.

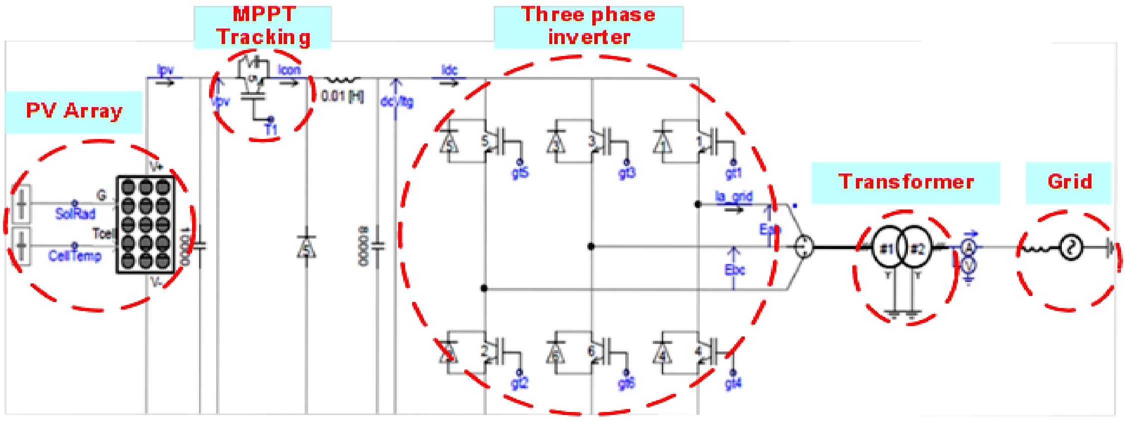

Fig 5. Grid connected PV system.

4.1Maximum power point tracking (MPPT)

The model used for creating the reference voltage is shown in Fig. 6. First, photovoltaic output current (I_{pv}) and output voltage (V_{pv}) are passed through a first order low pass filter with a magnitude of $G = 1$ and a time constant of $T = 0.1$ seconds in order to filter out the high frequency components. Filtered current and voltage signals (I_{pv}_F and V_{pv}_F) are then fed into the MPPT control block that uses the incremental conductance (IC) tracking algorithm. An algorithm that is based on the fact the slope of the PV array power curve is zero at the MPP, positive on the left of the MPP and negative on the right side of the curve. The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$). The MPPT generates a reference voltage (V_{mppt}) at which the PV array is forced to operate.

The algorithm decrements or increments V_{mppt} to track the maximum power point when operating under varying atmospheric conditions as shown in Fig. 7. This reference voltage V_{mppt} is used as an input to the DC-DC Converter Control model discussed next.

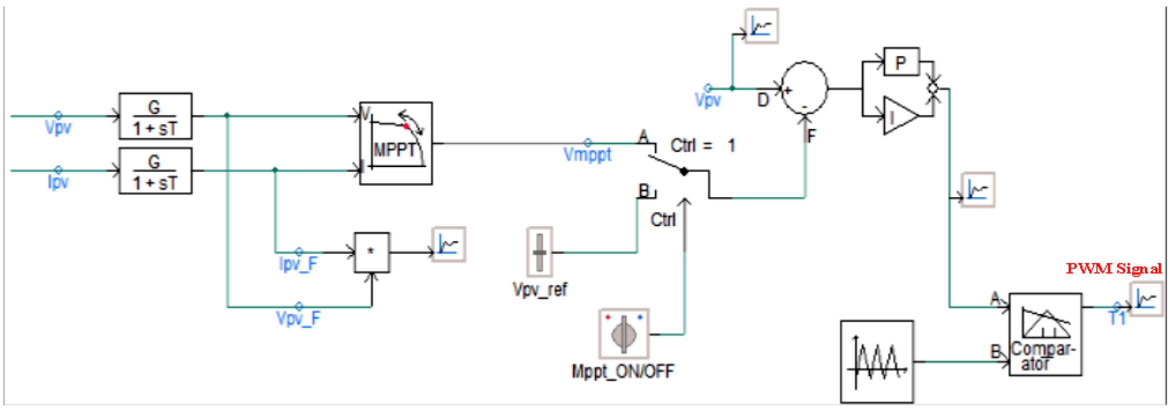

Fig 6. MPPT Tracking model and converter control.

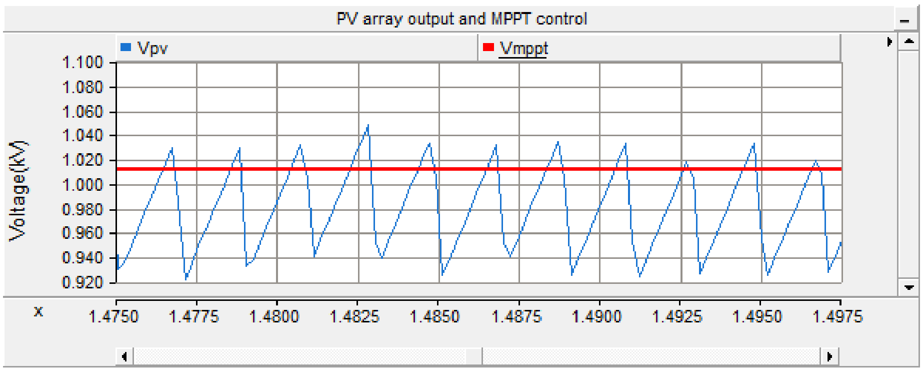

Fig 7. Input (V_{pv}) vs. V_{mppt}.

4.2 DC-DC converter control

DC-DC converter is an electronic circuit that is used either as buck converter or as a boost converter. In this model, buck converter was used that consists of a pulse width modulation (PWM) circuit shown in Fig. 6, Insulated Gate Bipolar Transistor (IGBT) switch, inductor, capacitor and free-wheel diode [6], as shown in Fig. 5. The difference between V_{pv} and reference voltage V_{mppt} is used as an input to the PI controller (shown in Fig. 6), which in turn based on this difference, controls the duty cycle of the PWM pulse. The duty cycle is fraction of the period during which the switch is on, ranges between 0 and 1. A duty cycle value of 1 means ON and OFF time are equal, a value greater than 1 means ON time is greater and vice versa [7]. The PWM signal (T_1) was generated by using a comparator which has the duty cycle signal at port A and a saw-tooth wave at port B which ranges from 0 to 1. The comparator sets its output to 1 whenever A is greater than B.

4.3 Three phase inverter

In order to be able to tie a PV system with the utility grid, the DC output power of the DC-DC converter should be converted into a three phase AC power using a three phase inverter. It is part of inverter's task to keep the DC voltage across its input (DC-DC converter's output) at a constant value. In this model, the three phase inverter consists of a cascaded control scheme for P and Q regulation, a firing pulse generator and a three phase inverter bridge as shown in Fig. 8.

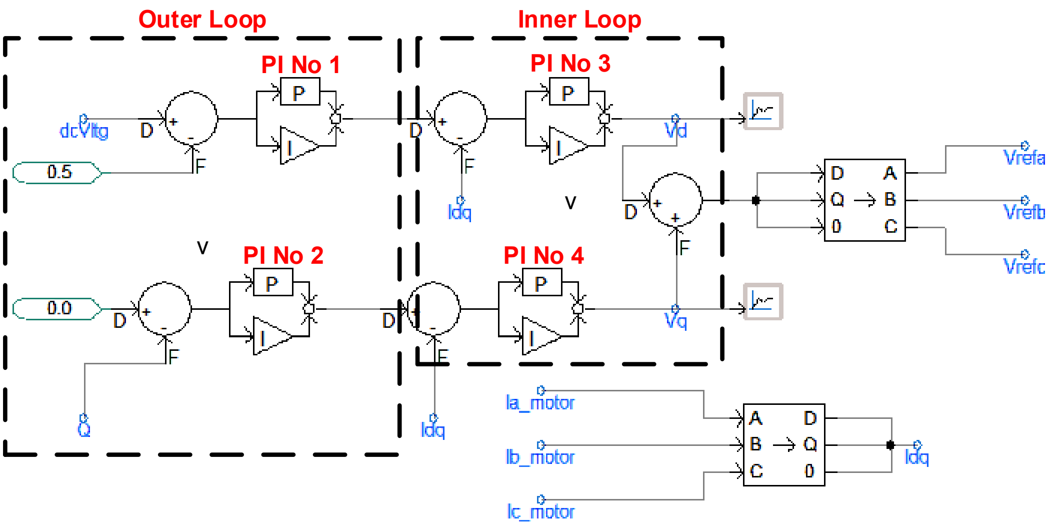

Fig 8. Cascaded control.

4.3.1 P and Q regulation

In order to establish a constant DC bus voltage (dcVltg) between the DC-DC converter and the inverter, four PI controllers cascaded scheme as shown in Fig 8 is used. The output of the PI-1 controller will be fed to summer which is added with converted DQ based current, fed from the inverter output current. After addition of these two signals they are added to PI-3 which directs it to final summer to give V_q. PI-2 and PI-4 combines to give reference voltage V_d, so the final voltages (V_q and V_d) are added up and thus finally converted to three phase voltages. Now scope of this paper is to fine tune these four PI controllers using Taguchi Approach [10] and evaluate its performance. The three outputs are now used as an input to the firing pulse generator which will be discussed next.

4.3.2 Firing pulse generation

The switching signals of the 6 IGBT switches of the 3- legged inverter bridge were generated using a sinusoidal pulse width modulation (SPWM) technique shown in Fig. 9. It starts with comparing three sinusoidal modulating waves with a triangular carrier wave magnitude ranging between -1 and 1. Switching signals gate (gt1), gt3 and gt5 were generated by setting the output of the comparator to 1 whenever the modulating wave is greater than the carrier wave and 0 otherwise. Since the operation of the two switches in each of the three legs of the inverter bridge should be complementary to produce the final sinusoidal wave, the switching signals gt4, gt6 and gt2 were generated by inverting the switching signals gt1, gt3 and gt5, respectively [8].

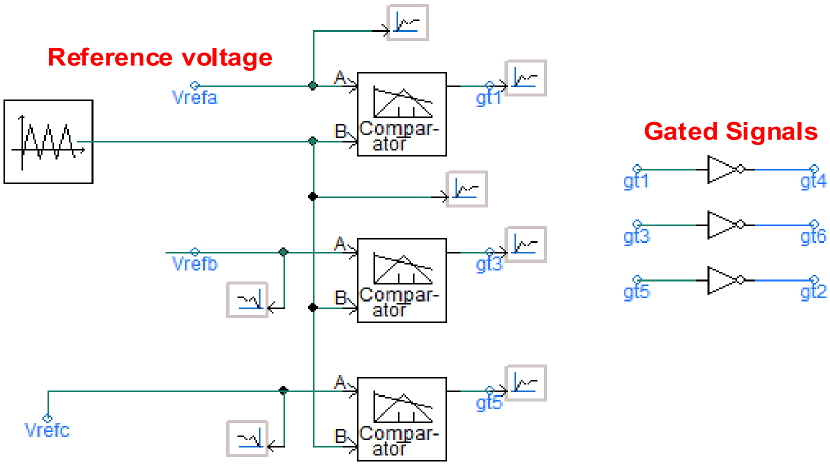

Fig 9. Firing pulse generation model.

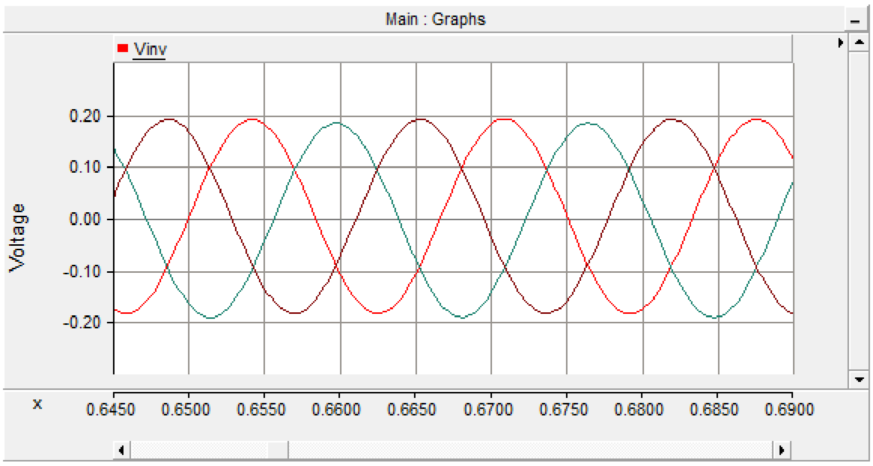

Fig 10. Inverter output voltage.

4.3.3 Three phase inverter bridge

By applying the previously generated switching signals (gt1 to gt6) to the 6 IGBT switches (Fig. 5), the inverter kept its output voltage at a constant value, as shown in Fig. 10, even when the irradiation increased from 200 W/m^2 to 1000 W/m^2).

4.3.4 Transformer

Transformers in grid connected PV systems act as galvanic isolation and can be used for voltage adjustment if required [9]. A conventional, 60 Hz, Y-Y, three phase step up transformer (230V/11kV) was used in the PSCAD model as shown in Fig. 5.

4.3.5 Utility grid

The utility grid system is represented only as an equivalent 11kV/230V, 60 Hz transformer that was connected to the inverter while the high voltage side (11 kV) was connected to the grid as shown in Fig. 5.

5. Cascaded control for inverter

The cascaded control for inverter is the most important component for integration of PV plant to the grid. In this paper Taguchi method is used for the three phase voltage source inverter control. The four PI control schemes (Fig.8) are tuned together using this technique. For this purpose a three phase fault is created at fault location shown in Fig.5. When a fault occurs, the inverter is unable to deliver power generated by the PV plant to the grid because of the drop in the grid voltage. The excess energy gives a sharp rise and inverter output voltage is assessed in per unit.

5.1 Taguchi approach

The design optimization process is presented for fine tuning the PI controllers' parameters using Taguchi method. In Taguchi method, an orthogonal array that depends on the number of factors and their levels is used to study the parameters variation effect [10]. For example, if there are four factors each at three levels, the full factorial design method requires experiments while

Taguchi method needs only nine experiments to obtain the optimal values.

In cascaded control design scheme four PI controllers are used. In establishing an orthogonal array, eight factors *A*, *B*, *C, D, E, F, G*, and *H* are considered. Where

A: Proportional gain of PI-1,
B: Integral time constant of PI-1,
C: Proportional gain of PI-2,
D: Integral time constant of PI-2,
E: Proportional gain of PI-3,
F: Integral time constant of PI-3,
G: Proportional gain of PI-4, and
H: Integral time constant of PI-4.

Table 1 illustrates the design variables or factors and their levels. The standard Taguchi's orthogonal array L-18 is used for this numerical study as shown in Table 2.

Table 1. Design variables and levels.

DESIGN VARIABLE	LEVEL 1	LEVEL 2	LEVEL 3
A	2.5	4	
B	0.4	0.6	0.8
C	1.5	2	2.5
D	0.4	0.6	0.8
E	0.7	1	1.3
F	0.008	0.0165	0.025
G	0.1	0.3	0.5
H	0.008	0.0165	0.025

Table 2. Actual values of settings of eight design variables.

EXP. NO	LEVEL OF EACH VARIABLE							
	A	B	C	D	E	F	G	H
1	2.5	0.4	1.5	0.4	0.7	0.008	0.1	0.008
2	2.5	0.4	2	0.6	1	0.0165	0.3	0.0165
3	2.5	0.4	2.5	0.8	1.3	0.025	0.5	0.025
4	2.5	0.6	1.5	0.4	1	0.0165	0.5	0.025
5	2.5	0.6	2	0.6	1.3	0.025	0.1	0.008
6	2.5	0.6	2.5	0.8	0.7	0.008	0.3	0.0165
7	2.5	0.8	1.5	0.6	0.7	0.025	0.3	0.025
8	2.5	0.8	2	0.8	1	0.008	0.5	0.008
9	2.5	0.8	2.5	0.4	1.3	0.0165	0.1	0.016
10	4	0.4	1.5	0.8	1.3	0.0165	0.3	0.008
11	4	0.4	2	0.4	0.7	0.025	0.5	0.0165
12	4	0.4	2.5	0.6	1	0.008	0.1	0.025
13	4	0.6	1.5	0.6	1.3	0.008	0.5	0.0165
14	4	0.6	2	0.8	0.7	0.0165	0.1	0.025
15	4	0.6	2.5	0.4	1	0.025	0.3	0.008
16	4	0.8	1.5	0.8	1	0.025	0.1	0.0165
17	4	0.8	2	0.4	1.3	0.008	0.3	0.025
18	4	0.8	2.5	0.6	0.7	0.0165	0.5	0.008

5.2 Ziegler Nicholas approach

The Ziegler–Nichols tuning method is a heuristic method of tuning a PI controller. It is performed by setting the integral (K_i) and derivative (K_d) gains to zero. The proportional gain, K_p is then increased (from zero) until it reaches the ultimate gain K_u, at which the output of the control loop oscillates with a constant amplitude. K_u and the oscillation period T_u are used to set the P, I, and D gains depending on the type of controller used. But this method it fails to work well when the processes are high-order and nonlinear [11].

5.3 Grid codes

Germany and IEEE grid codes are dominant in PV market and therefore the German and IEEE regulations issued by the VDE Testing and Certification Institute, Germany and IEEE are very important. The German code VDE 0126-1-1 includes over/under voltage and frequency detection and describes the test procedures for a fail-safe protective interface that has to disconnect automatically the PV inverter from the grid in case of DC injection, fault current and low isolation to earth and IEEE 1547 specifies grid integration with distributed sources [6]. All these codes are of importance for LVRT.

5.4 Dynamic analysis

The PV system may have to be disconnected when its terminal voltage drops below the specified threshold voltage, e.g. 70% of the nominal voltage. This disconnection is mainly to protect the inverter. However, it also impacts on the transient state of the power system. The capability of the PV system to ride through the faults is determined by LVRT characteristics. The requirement of this LVRT varies from system to system depending on the grid code. The influence of LVRT characteristics of high-penetration PV generation on the transient stability is presented in [12].

Simulations are performed to determine LVRT characteristics by considering a symmetrical 3LG and unsymmetrical 2LG and 1LG faults at fault location shown in Fig. 5 using PSCAD/EMTDC. Simulation time is 30s and fault simulation time is considered as 3s. The fault is considered at 0.1 s; duration of the fault is 0.5s All the simulations are done for standard test condition (1000 W/m^2 and 25ºC) [13].

6. Results and discussion

Time domain simulation has been carried out using PSCAD/EMTDC. The grid code is fair important to analyze the transient characteristics of the photovoltaic plant. As mentioned earlier, in this study, an optimum design of cascaded PI controller's parameters is determined by the fault ride through under various fault conditions. The grid code [6] is taken into consideration to evaluate the performance of grid-side voltage. During steady state condition, DC link rated voltage is 0.5 kV. In all cases the voltage returns to the nominal voltage within 0.5s after fault is recovered. Hence, the grid code mentioned in [6] can be met with the control strategy used in this paper.

In simulation analysis, the 3LG, 2LG and 1LG faults are considered as the network disturbance. The fault occurs at 0.1s and duration of fault is 0.5s at fault location shown in Fig 5.The responses of the grid-side terminal voltage during 3LG, 2LG and 1LG faults are given in Fig. 11.This approaches can augment the fault ride through capability of the Inverter. It is found from the simulation results that Taguchi approach is better than Ziegler-Nicholas method to design eight design variables of four PI controllers in a cascaded control scheme. It is also shown that Taguchi approach gives better response in terms of fast voltage recovery as per grid code requirement [14]. It also gives lower oscillations as obvious from the output responses.

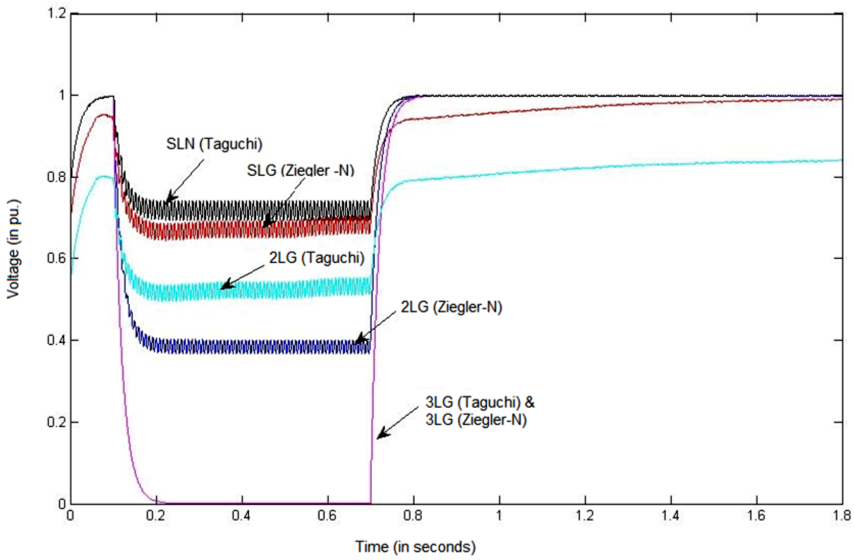

Fig 11. Grid side voltage (3LG, 2LG and 1LG Fault).

7. Conclusion

In this study, an optimum design procedure for a cascaded control scheme using multiple PI controllers has been presented and fine-tuned using Taguchi approach and Ziegler-Nicholas method. It is verified by ride through the faults determined by low voltage ride through (LVRT) characteristic. Furthermore tasks of the different components of the model were discussed. The control stages involved in generating the switching signals using PWM and SPWM for DC-DC converter and inverter, respectively, were tracked using the PSCAD model. Finally, it is concluded that the proposed coordinated control scheme can successfully augment the LVRT capability of DC-based PV plant under various fault conditions as required by the recent grid codes.

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