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OPTIMUM PROTECTION STRATEGY OF PV SYSTEMS AGAINST LIGHTNING INDUCED FAULTS

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Abstract: The incidence of lightning discharges and efficient protection of photovoltaic electrical networks against induced faults has been a crucial problem. A common method for solving this problem is to install surge protection devices in the photovoltaic electrical network. However, for a large PV electrical system, a great challenge is to find critical points in the network where surge protection devices can be installed to adequately protect the total photovoltaic electrical network while keeping the total number of installed surge protection devices at a minimum. To solve this challenge, this paper presents a method for the optimization of photovoltaic network protection using the genetic algorithm optimization method to find specific points for the installation of a minimum number of surge protection devices while maximizing the number of protected equipment in the network. The photovoltaic system is modeled and simulated using mathematical laboratory/Simulink (i.e. MATLAB/Simulink). The results obtained showed that at lightning strike, the voltage levels in the photovoltaic network were kept within acceptable limits while minimizing the number of surge protection devices used. Thus, it can be concluded that the genetic algorithm (GA) protection optimization method is effective for a large photovoltaic network.
Keywords: Genetic algorithm; Surge protective device; Lightning discharge; Photovoltaic system

INTRODUCTION

This paper presents a method for the optimum protection strategy of photovoltaic systems against lightning induced faults. The objectives of this research are to establish the effects of lightning discharge on photovoltaic network, model the case study photovoltaic network and develop a method for the strategic placement of surge protective devices in a given photovoltaic network. Lightning discharge is a transient current pulse. It is a short-lived phenomenon and it is observed that a single strike is consisting of several small strikes of different properties. Lightning is capable of injecting overvoltage transients into DC networks resulting into undesirable effects on direct current (DC) equipment including photovoltaic (PV) cells (Shahniaand, F. et al, 2006).

In the 1980s, photovoltaics became a popular power source for consumer electronic devices, including calculators, watches, radios, lanterns and other small battery-charging applications. Following the energy crises of the 1970s, significant efforts also began to develop PV power systems for residential and commercial uses, both for stand-alone, remote power as well as for utility-connected applications. During the same period, international applications for PV systems to power rural health clinics, refrigeration, water pumping, telecommunications, and off-grid households increased dramatically, and remain a major portion of the present world market for PV products. (Florida Solar Energy Center, 2007).

Photovoltaic (PV) systems are susceptible to failures from atmospheric discharges that could interrupt the normal operation of converting solar energy to electrical power energy. Atmospheric discharges are able to cause failures on PV systems mainly due to expanded surface areas, installation in wide-open areas and elevated heights. PV systems can experience large discharge of energy from a lightning strike and electromagnetic interference due to the coupling elements of the PV systems which include cables, solar module metallic frame, earthing system, etc (Fallah et al, 2013).

In many parts of the world where PV systems are installed, most designers and installers ignore the likelihood of lightning discharge in the area which could induce faults in the systems, thus the PV systems are not adequately protected against lightning induced faults (Ittarat, S. 2013). Lack of adequate protection on the systems can induce faults on systems thereby incurring an avoidable cost of repair. Accumulated cost of repair is eventually higher than the cost of providing an adequate protection on the systems. Inadequate or lack of protection can also increase the time of the return of investment on the PV systems (Ehrhardt, A. et al, 2014). Therefore, it is necessary to incorporate an appropriate lightning protection system (LPS). However, the avoidance of lightning is not adequate as lightning current passing through an LPS may induce faults in the PV system due to inductive coupling. Thus, PV systems should be strategically placed and the insulation of conducting components wherever possible should be done (Kern, A. et al, 2004 , Fallah et al, 2013 & Spooner, E. 2001).

Various methods of lightning protection have been investigated, developed and applied. The earliest described method of lightning protection was the Franklin rod system proposed by Lichtenberg, G.C in 1778. This system consists of 3 main parts: Air terminal, Down conductor and Ground terminal. In 1876, James Clerk Maxwell suggested the Faraday Cage approach of protection in which case the lightning current is constrained to the exterior of the cage and it is not necessarily grounded (Vladimir, A.R 2017).

COMMON PV PROTECTION PRACTICES

Empirical methods based on statistics and experiments were employed in evaluating the need for protection and protection levels of PV installations against lightning induced faults over varying potential situations. In a method, two levels of lightning protection measures have been defined for optimum protection of PV systems for various PV installation situations. These are Protection Level A for common lightning risk and Protection Level B for high lightning risk. For protection level A. all exposed conductive parts are interconnected and then properly connected to the ground; individual components are not to be independently connected to the ground. The external protection by varistors on DC and alternating current (AC) circuits is then implemented. Specific protection is provided on other external lines such as telephone lines with no direct link to the PV system. Protection level B, the ground conductors of individual components are interconnected, thereafter properly connected to the ground. External protection by varistors is also provided on DC connections of the installation while appropriate protection is staged on AC aerial grid if present. The shielding of sensitive cables is also done to provide a comprehensive Level B protection for high lightning risk (Lea, P. 2003).

Similarly, a template for the optimum protection of structures adopting the external protection system only was developed. In practical terms, the external lighting protection system consists of an air termination, down conductors and ground electrodes. However, the basic installation of the protection system may not adequately provide protection for the structures when the attractive radius of the structure to lightning extends beyond that of the protection mast. Therefore, the researcher adopted the rolling sphere principle in optimizing the external protection system allocation. In the rolling sphere principle, a sphere is rolled over the protecting structure and areas which the sphere cannot touch are within the protection zone. The radius of the sphere varies between 20 and 60 m depending on the degree of protection required. The researcher however, established a standard radius of 45m wherein an increased degree of protection can be obtained by the reduction of the radius. (Fallah et al, 2013).

The use of Surge Protective Device (SPD) is also a common choice for the protection of PV installations. SPDs installation in a method, is performed as close to the terminals of the equipment. In order to achieve optimum internal protection, three classes of SPDs and respective installation application are defined: SPDs type I, which provide primary protection against 10/350µs lightning current and are installed mainly at the entry point of the installation at the borders between lightning protection zone 0 to 1 (LPZ 0–LPZ 1), representing zones outside the structure and zone in the structure respectively. SPDs type II provide protection against 8/20µs surge currents and are installed at main node points of the installation at the borders between LPZ 1–LPZ 2, with LPZ2 representing the inverter unit. SPDs type III provide fine protection against 8/20µs surge currents and 1.2/50µs surge overvoltages and they protect sensitive electronic devices from impact by lightning striking far away. Type III SPDs should always be installed at least after type II SPDs. (Tong, C. et al, 2014 & Pons, E. et al, 2013).

MODELING AND ANALYSIS

The solar PV system was modeled in the MATLAB Simulink environment. The components of the PV system model include the PV cell array, buck converter, charge controller, battery and inverter. The nodes to be analyzed for voltage surge are identified as points between each component in the PV network. A line diagram showing connected components and nodes is shown in Figure 1.

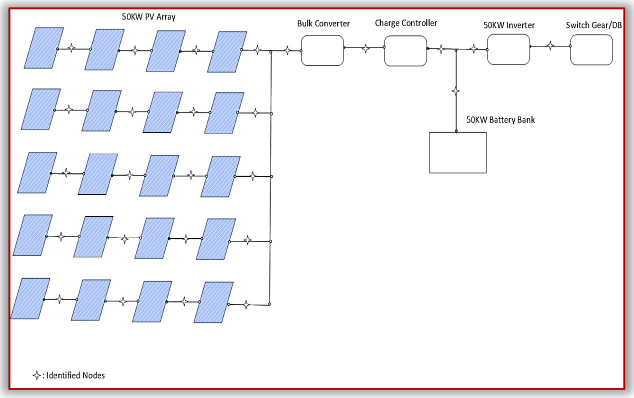


Figure 1. PV Model Under Case Study Showing Identified Nodes

The predefined PV model block available in the Simulink library is used with an irradiance value of 1000 and temperature value of 25 degrees Celsius.

The buck converter as shown in Figure 2 acts as a regulator to convert the DC input from the array of PVs to either a higher amount of DC or a lower amount of DC as required by the system for the charging of the battery system or the conversion of the DC power to AC power by the inverter system (Esram, T. et al, 2007). The buck system is built up of a high-power inductor coupled with a small value resistor, a insulated-gate bipolar transistor

(IGBT) switching component, snubber diode and a coupled resistor-capacitor component for the input and output terminals of the buck converter. The IGBT duty cycle is controlled by an input signal, s_boost from the pulse width modulation (PWM) generator.

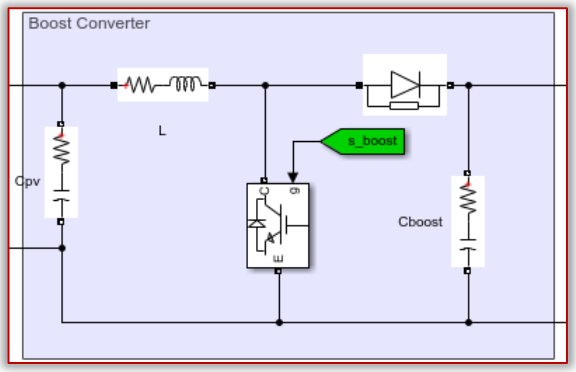


Figure 2. Buck Converter

The current (I) and voltage (V) characteristics of a PV cell is non-linear under certain irradiance and temperature. Therefore, it is necessary to automatically find an optimum I and V point at which maximum power can be achieved from the PV cell in a process called Maximum Power Point Tracking (MPPT) (Esram, T. et al, 2007). This thesis has adopted the perturb and observe (P&O) maximum power point tracking (MPPT), which is effective in tracking and ease of implementation. The P&O MPPT Simulink circuit implementation is shown in Figure 3.

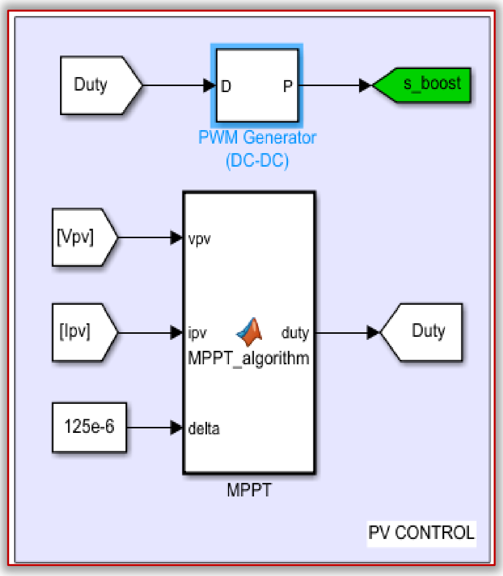
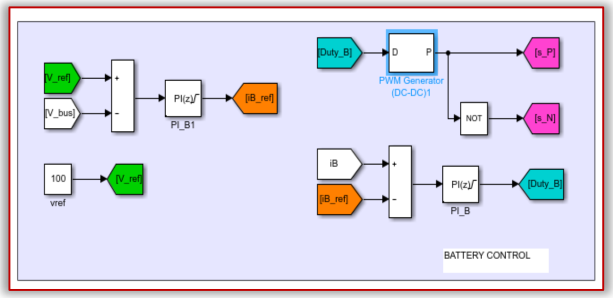


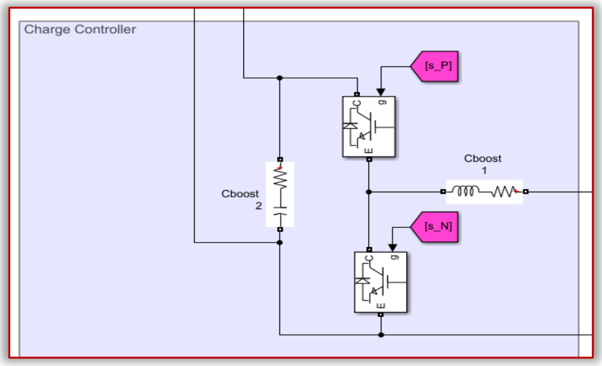
Figure 3. Perturb and Observe MPPT

The MPPT algorithm is scripted to implement a trial-and-error process in finding the maximum power point. The algorithm monitors for changes in power and perturbs operating voltage of the solar PV panel by changing the duty cycle to the switching device of the inverter and the buck converter in a repeated process until maximum power point is reached.

The battery charge controller as shown in Figure 4 monitors the battery current and voltage parameters to determine the duty cycle of the charge controller. The battery control device compares the battery voltage level against a voltage reference. If the voltage level of the battery is less than the reference voltage, the proportional integral (PI) controller outputs an error signal which is taken as the battery current reference. The current reference is then compared with the battery current via the second PI controller. This error signal obtained is fed into the input of the PWM generator as the duty cycle. The duty cycle is used to determine the percentage of the pulse period that the output is on. A branch is taken from the PWM output and inverted to yield two outputs [s_P] and [s_N] of opposing signals at a given time, thereby delivering charging current to the battery as required.



(a)

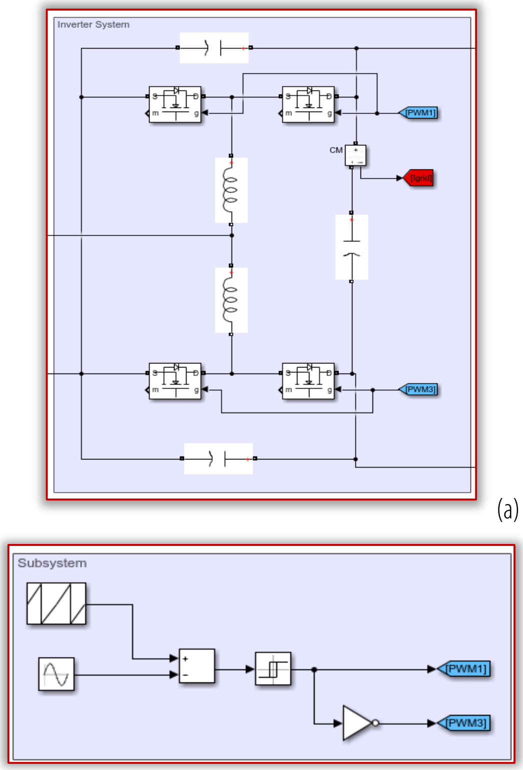


(b)

Figure 4 (a) Battery charger Controller (b) Charge Controller

The inverter model used in this thesis is a single-phase, full bridge, sine wave inverter. It is modeled using 4 metal-oxide-semiconductor field-effect transistor (MOSFETs), 3 capacitors and 2 inductors connected as shown in Figure 5 (a). Each MOSFET has internal diode resistance of 0.01 Ohms, the capacitors value is 0.006F each and inductors value of 0.003H. The switching circuit that controls the MOSFETs is as shown in Figure 5 (b). It consists of a sawtooth generator block, sine wave generator block, a relay block and a NOT logical operator block.

The lightning simulator circuit is built with a network of components as shown in Figure 6. The circuit consists of a DC source, resistors, capacitor, pulse generator, and a gate-controlled switch. The DC voltage is set to 100kV, capacitor value set to 10e-6 F, resistors have values of 240k, 1.2k and 0.24k Ohms.



(a)

(b)

Figure 5 (a) Single Phase Full Bridge Inverter (b) MOSFETs Switching Circuit

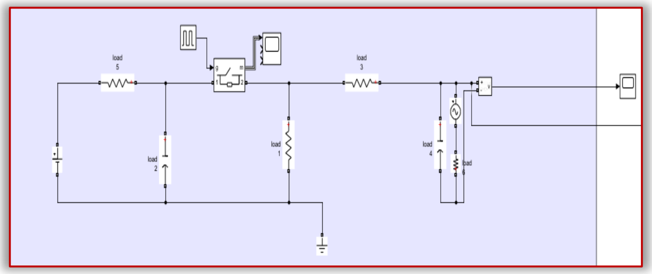


Figure 6. Lightning Simulator Circuit

GENETIC ALGORITHM

The Genetic Algorithm flowchart for the optimum allocation of SPDs is presented, as shown in Figure 7.

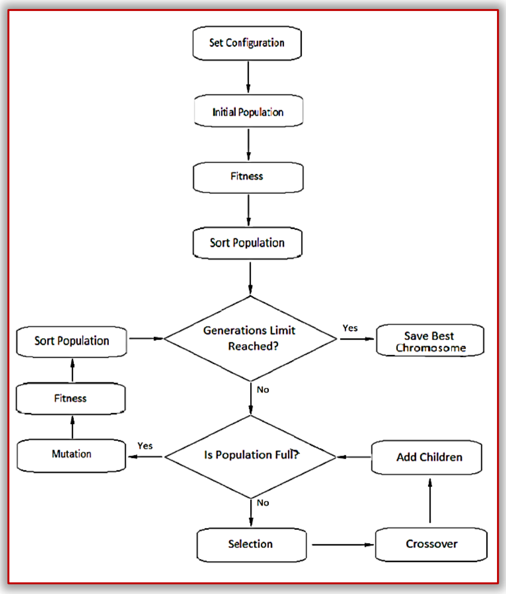


Figure 7. Genetic algorithm flowchart.

The program starts with the desired configuration such as the size of the population, generation limit, mutation and fitness, all of which determine the run time of the program to reach a desired solution.

Chromosome represents a solution to be tested as a probable optimal solution to the problem of optimization. Each gene represents a network node that is candidate to receive a surge protection device. The number of chromosome genes is equal to the total number of electric nodes in this case study. In order to run the genetic algorithm successfully, the genes are encoded from real values to discrete values which are in this case, binary values of 0s and 1s. The population is a set of chromosomes that form a set of genetic algorithm generation, which will undergo changes via mutation and crossover in the course of the program. The population size for this study is set to 4 as shown in Figure 8. The genes of the chromosomes have been stochastically generated while ensuring that no chromosome is set to extreme maximum (i.e. all genes set to 1) and extreme minimum (i.e. all genes set to 0). Setting chromosomes to extreme maximum and minimum can considerably increase convergence time which is undesirable and also prove counter intuitive since the aim of optimization is to use the least possible number of surge protection devices to protect the maximum number of equipment possible in the PV system. An example of the chromosomes is as shown in Figure 8.

1	1	0	0	1	1	0	0	1	1	0

1	0	1	0	1	0	1	0	1	0	1

1	1	1	0	1	1	1	0	1	1	1

1	0	0	0	1	0	0	0	1	0	0

Figure 8. A population set showing chromosomes

The fitness of the genetic algorithm, in which the created initial chromosomes are tested, is then critically determined. Since the aim of protection is to prevent induced faults due to lightning induced overvoltage and overcurrent, it means that the system will maintain a certain voltage limit beyond which it is considered unsafe for the system. For this study, the voltage beyond which a fault can occur is termed **Vlimit** and is set to 260V. When the chromosomes are tested with lightning induced voltages, and the system voltage remains within the **Vlimit** of 260V, the chromosomes are considered fit. Thus, this is considered the first test for fitness which is tested by running the simulation via MATLAB Simulink. The first fitness equation is given in Equation 1.

$$\mathrm{Vlimit} \leq 260\mathrm{V} \qquad (1)$$

The second fitness equation is composed of the sum of two terms. The first term E consists of evaluating the percentage of equipment that has been protected according to Equation 2. Protected equipment is one whose electrical node has electric voltage level within the **Vlimit**.

$$E = \frac{E_{total} - E_{over}}{E_{total}} \times 100 \qquad (2)$$

Where E_{total} is the total number of equipment in the PV network, E_{over} is the total number of equipment that is connected at electric nodes that have exceeded the **Vlimit**.

The second term S evaluates the number of surge arresters that were required to perform the optimal allocation as shown in Equation 3.

$$S = \frac{S_{desired} - S_{allocated}}{S_{max} - S_{desired}} \times 100 \qquad (3)$$

Where S_{max} is the maximum number of surge protection devices that can be allocated in the electrical PV system. $S_{desired}$ is the user-defined number of arresters to be allocated and $S_{allocated}$ is the amount of allocated surge arresters by the genetic algorithm procedure.

The final fitness equation is defined by Equation 4, as the weighted sum of the terms E and S. It is possible that the weighted sum in Equation 4 generates a negative value, and in this case the fitness value will be set to zero.

$$\text{Fitness} = \max(E + S) \qquad (4)$$

Further to the chromosomes evaluation by the fitness function, two best chromosomes are selected using the proportionate selection method in which chromosomes with the highest fitness scores are selected as parent to generate a new pair of chromosomes in a process called the Crossover. The single point crossover solution is used where half the genes of the parents' chromosomes is taken to create a child chromosome. The crossover method is illustrated in Figure 9.

Parent Chromosomes

Parent 1A					Parent 1B					
1	1	0	0	1	1	0	0	1	1	0
Parent 2A					**Parent 2B**					
1	0	1	0	1	0	1	0	1	0	1

Child Chromosomes

Parent 1A					Parent 2B					
1	1	0	0	1	0	1	0	1	0	1
Parent 2A					**Parent 1B**					
1	0	1	0	1	1	0	0	1	1	0

Figure 9. Parent to Child chromosome Illustration

Thereafter are the child chromosomes mutated using the point mutation in which only one random bit or gene is changed. This is as illustrated in Figure 10.

Child Chromosome

1	0	1	0	1	1	0	0	1	1	0

Mutation

0	1	1	0	1	1	0	0	1	1	0

Figure 10. Child Chromosome Mutation Illustrated

ANALYSIS

The final chromosome generated by the genetic algorithm program is given as [0 0 1 0 1 0 1 1 0 0 1]. By comparison to the nodes on the PV network [a b c d e f g h I j k], the solution presented by the genetic algorithm suggested that 5 SPDs be installed on nodes C, E, G, H and K.

From the result obtained, it could be deduced that all equipment was adequately protected, therefore, the percentage of equipment protected according to Equation (2) is evaluated as:

$$E = \frac{E_{total} - E_{over}}{E_{total}} \times 100$$
$$E = \frac{24 - 0}{24} \times 100$$
$$E = 100$$

The percentage of SPDs used according to Equation (3) is evaluated as:

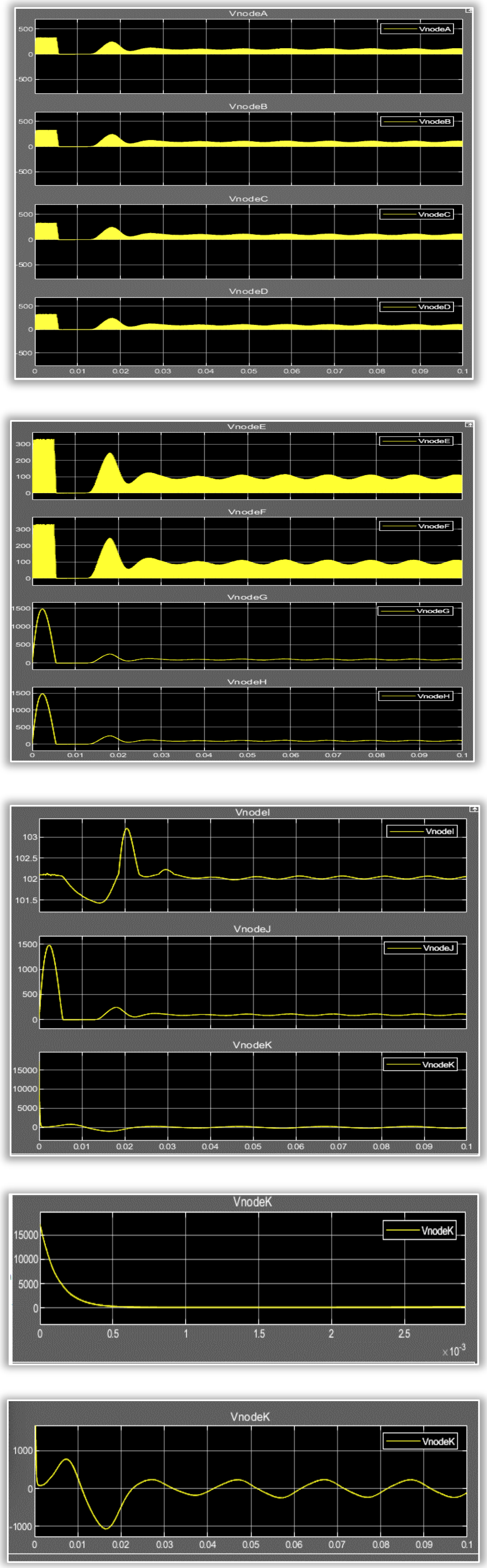
$$S = \frac{S_{desired} - S_{allocated}}{S_{max} - S_{desired}} \times 100$$
$$S = \frac{7 - 5}{10 - 7} \times 100$$
$$S = 66.7$$

The genetic algorithm program run made a maximum fitness score of 166.7.

DISCUSSION OF RESULTS

At normal operations, it is observed that the PV output levels are relatively stable and averaging 100V. All nodes of the PV system connected in parallel have the same output levels as expected. The steady voltage is maintained across the charge controller, battery, nodes G,H,I,J and Inverter input ports. The sine-wave output from the inverter maintains 240V.

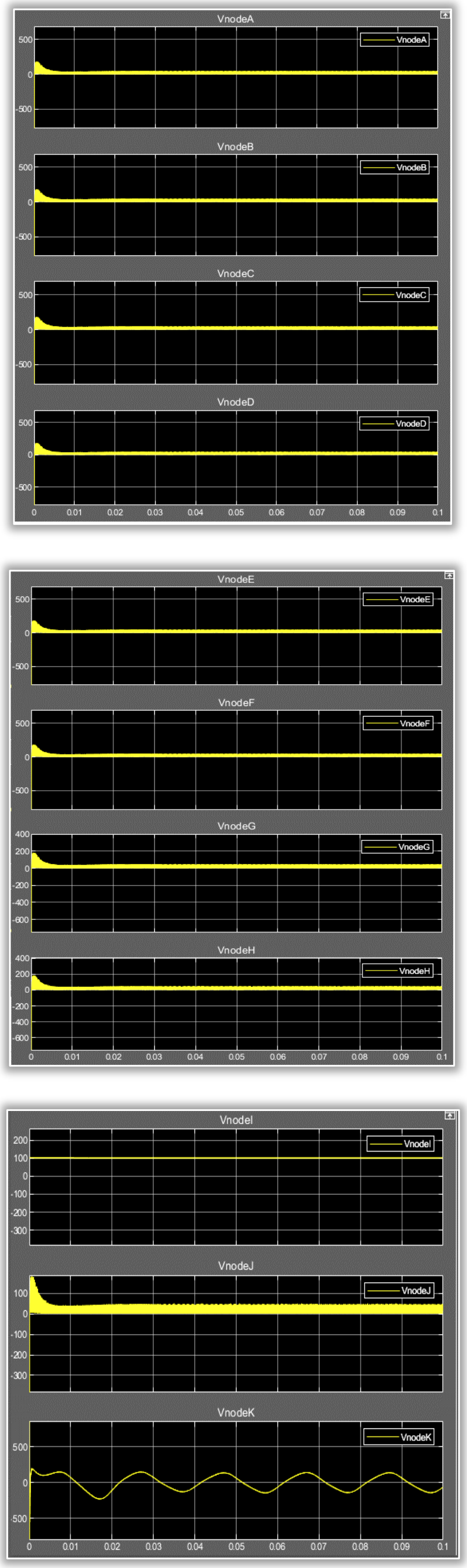
At lightning strike condition on a critical node J, an unwanted surge in voltage was propagated through the photovoltaic network. The results shown in Figure 11 (a) & (b) indicated a surge exceeding 300v that lasted for about 0.005sec on the PV array nodes. Afterwards the voltage was at zero level and at about time 0.014 sec of the simulation, a second surge of about 250v was recorded. The recorded high voltages are dangerous for the solar panel arrays which 100v average output is expected. At nodes G, H and I beyond the buck converter, the resulting surge was as high as 1.5kV for a period of 0.005 sec as shown in Figure 11(b). Node I which connects to the battery recorded an unusual waveform as seen in Figure 11(c). The DC voltage was forced into a sinusoidal waveform for a short duration. Node K, at the inverter output recorded the highest surge in excess of 15kV, settled in less than 0.002 sec which was then followed by a second sinusoidal surge of about a thousand volts which lasted for about 0.02 sec as shown in Figure 11(d).



(a) (b) (c) (d)

Figure 11. Graph showing levels with lightning discharge (a) at nodes A-D (b) at nodes E-H (c) at nodes I-K (d) at node K scaled to show portions of peak levels

With Genetic Algorithm applied, the results obtained at lightning strike are as shown in Figure 12.



(a) (b) (c)

Figure 12. Graph showing levels (a) at nodes A-D (b) at nodes E-H (c) at nodes I-K with lightning discharge and genetic algorithm optimum solution

It could be observed that the genetic algorithm optimally allocated SPDs that successfully reduced the lightning induced overvoltages, thus keeping the network protected. The voltage levels across all nodes were kept at an acceptable limit of 200v for the DC side and 250v for the AC side of the inverter. At the end of the program run, the genetic algorithm allocated 5 SPDs out of a set limit of 7 SPDs.

CONCLUSION

A method combining the use of genetic algorithm optimization method for the optimum protection strategy of photovoltaic systems against lightning induced faults, by the strategic allocation of SPDs and the consideration of lightning discharge incidence on identifiable critical nodes is presented. The genetic algorithm optimization, applied in the strategic allocation of surge protective devices proved effective, obtaining very good results with respect to reducing overvoltages at all nodes of the network, ultimately protecting the network from lightning induced faults.

This method allows the effective planning of the protection of PV systems to be met while keeping the financial investments at minimum in surge protection devices for the network. The results indicated that the proposed method is applicable in real world protection applications that cut across large and dynamic PV systems, serving as a guide in surge protection devices allocation and planning.

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