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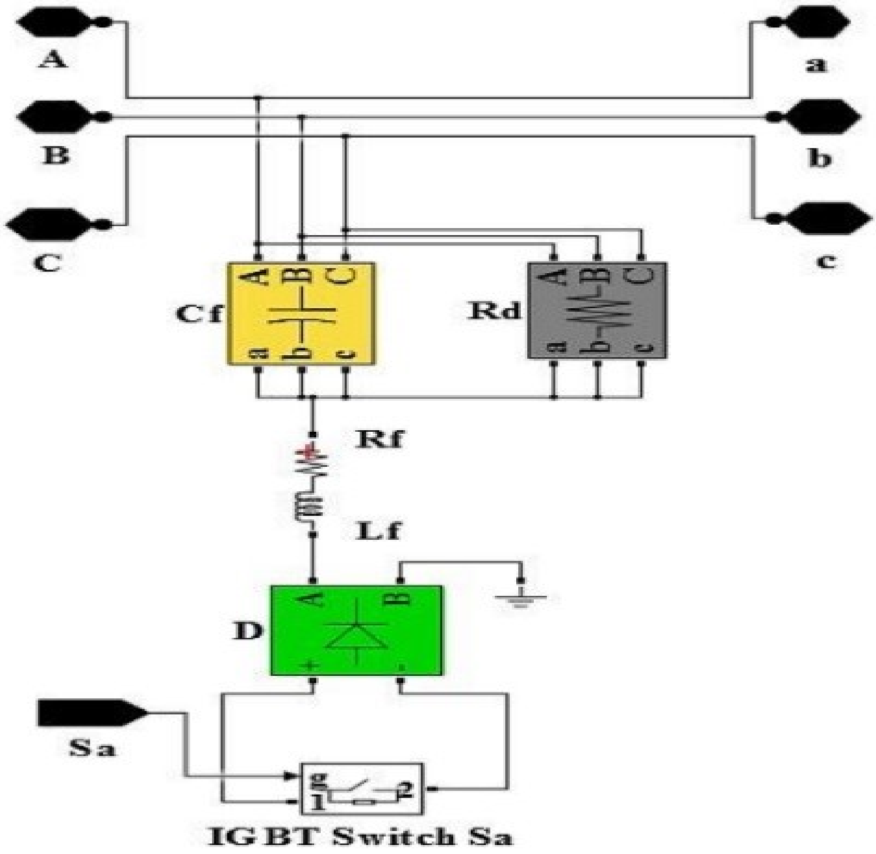

TURKISH JOURNAL OF ELECTROMECHANICS AND ENERGY

VOLUME 1 NO 1

ISSN 2547-975X

2016 January-June Issue

SCIENCE LITERATURE

Kazım Karabekir Work-Center, F:3/C/196, 50. Year Street, Lalapaşa Neighborhood, Yakutiye, Erzurum, Turkey

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Turkish Journal of Electromechanics & Energy

ISSN: 2547-975X

Editorial

Introducing "Turkish Journal of Electromechanics & Energy"

"From the North of Turkey to the World"

2016

We are delighted to announce the birth of Turkish Journal of Electromechanics & Energy (TJEE) which is publishing its first issue after two years long of preparation. Even though journal name is quite specific, the TJEE is intended to provide a platform for researchers at the cross-road of applied sciences from electrical engineering to mechanical engineering, materials science to physics of nature, chemistry to energy applications, etc. to share their work without limitation. The TJEE believes that dissemination of knowledge should be free-of-charge when the real owners of the work would like to share their findings with the science community. The whole TJEE staff team is of the same belief and is ready to work with self-sacrifice to this goal.

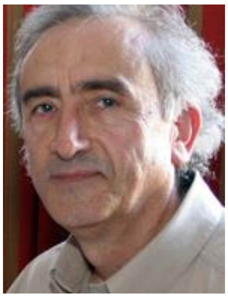
Several motivations contributed to the establishment of TJEE. The most important one is the increasing difficulty for researchers to publish their research results. Ever-changing requirements in journals regarding with manuscript preparation, long review, and submission-to-publication times are just a few of those. In addition, elevated number of submissions forced journal editors to become too-picky resulting in harsh criticism on submitted manuscript and reject those without even sending it to reviewers. Acceptance rate of received submission can be as low as 8% in some cases [1]. In such cases, "lack of novelty or limited contribution to the existing knowledge" is one of the most commonly used argument by editors to dismiss the manuscript at the very first glance, discouraging the authors in most cases [2]. TJEE would like to follow a different route; constructive criticism will be a key priority when evaluating received submissions.

As the TJEE aims to provide a common pavilion for multidisiplinary researchs and researchers, an editorial board have been formed from the experts with have different backgrounds, and interdisciplinary research experience. We thank them for accepting our invitation, invaluable suggestions and their time. The following is brief introduction of our editorial board members.

Dr. Adel Mahmoud SHARAF *specialized in power electronics applications in renewable energy matters. He obtained his Ph.D in Electrical Engineering from University of Manitoba, Canada in 1979. He joined Trans-Alta Utilities Corporation (Calgary, Alberta) in 1979 as a inductive coordination and planning engineer. Dr. Sharaf was selected as an NSERC-Canada research-assistant professor in 1981 at the University of Manitobai; then he joined the University of New Brunswick in 1981 as an assistant professor. He was awarded tenure in 1986 and full professorship in 1987. Professor Sharaf* *authored and co-authored over 720+ scholarly technical journals, conference papers. He also advised/supervised 50 graduate students (13 Ph.D and 37 M. Sc). He is currently president of Sharaf Energy Systems, and Intelligent Environmental Energy Systems, Incorporated, a Research and Development and Engineering, consulting companies incorporated in the Province of New Brunswick, Canada.*

Dr. Muammer KOÇ *is Director and founding professor of sustainability at Hamad Bin Khalifa University, QATAR since 2014. He held professor, director, chair and dean positions at different universities in Turkey and the USA between 2000-2014. He has Ph.D. degree in Industrial and Systems Engineering from the Ohio State University (1999) and an Executive MBA degree from the University of Sheffield, UK (2014). He has 130+ peer-reviewed journal, and conference publications; organized, chaired, and co-chaired various international conferences, workshops and seminars on design, manufacturing and product development. He has taught courses across a range of subjects, including product/process/business innovation and development; medical design and production; energy and efficiency; computer-aided engineering, design and manufacturing; modern manufacturing technologies; manufacturing system design; material forming plasticity; and the mechanical behavior of materials. His recent books are Hydroforming for Advanced Manufacturing (Woodhead Publishing, 2008), Design and Manufacturing of Micro-Products (Wiley, 2011).*

Dr. Mitra DJAMAL *is professor at the Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, INDONESIA. He graduated with B.Sc. degree from Institut Teknologi Bandung in 1984, and was awarded with the Doctor in Electrical Engineering (Dr.-Ing) degree by Institute of Measurement and Automation Engineering, Faculty of Electrical Engineering, Federal Armed Forces University, Munich, in 1992. He is also president of Indonesian Physical Society. He has 180+ publications in various journals and conferences. His research interests are sensors and sensor systems, smart home technologies, and mobile robots.*



Dr. Yaşar DEMİREL *obtained his PhD degree in chemical engineering from the University of Birmingham, UK in 1981. Prior to joining the faculty of the University of Nebraska (Lincoln, NE, USA) in 2006, he worked at the Cukurova University (TURKEY, 1982-1993), King Fahd University of Petroleum and Minerals, (SAUDI ARABIA, 1993-2000), and promoted to professor in 2000. He also carried out research and scholarly work at the University of Delaware (DE, USA, 1999-2001); and was visiting professor at Virginia Tech (Blacksburg, VA, USA, 2002-2006). His research interests include sustainable process design, simulation and optimization, energy technologies, thermodynamic analysis, technoeconomic and life cycle analyses, He is the editor-in-chief of the International Journal of Thermodynamics and listed in various editorial boards of international journals. Dr. Demirel authored and co-authored two books, four book chapters, and more than 160 research papers. His book titled Nonequilibrium Thermodynamics was published by Elsevier in 2014 in its third edition. The book titled "Energy: Production, Conversion, Storage, Conservation, and Coupling by Springer was published in its second edition in 2016. He has obtained several awards and scholarships, and presented invited seminars.*

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Dr. Youcef Soufi *is associate professor at the Department of Electrical Engineering at Université de Béjaïa, Bejaïa, ALGERIA. He obtained B.Eng. (1991) and Doctorate degrees from the University of Annaba, and the Magister degree in 1997 from University of Tébéssa, (ALGERIA) in Electrical Engineering. His current major research interests include electrical machines, diagnostic, wind and solar energy, power electronics and drives Applied to renewable and sustainable energy. He has 80+ technical papers in scientific journals and conference proceedings since 2000. He is currently in editorial board of 4 journals, and the member of technical program committee / international advisory board / international steering committee of 12 international conferences.*

Dr. Halil İbrahim OKUMUŞ *Associate Professor at the Department of Electrical & Electronics Engineering in Karadeniz Technical University, Trabzon, TURKEY. He received his B.Sc. degree in Electrical & Electronics Engineering from Karadeniz Technical University (KTU) and Ph.D. from Bristol University , UK, in 1992, and 2001, respectively. He is a senior Member of IEEE Power Electronics Society. He is member of the Chamber of Electrical Engineers in Turkey. His main research is intelligent control of power systems and utilization of renewable energy.*

Dr. Fareeha ZAFAR *Professor of Computer Science at Government College University Lahore, PAKISTAN. She earned her Ph.D in Computer Sciences specialized in mobile cellular networks from University of Derby- United Kingdom. She has been recently appointed as full professor at Department of Computer Science, University of Nigeria, Nussukka. Dr. Zafar, at present, is Research Head for Mobile & Communication Advencements. She has published 162+ journal articles and books published with Springer. She is also associate to multiple foreign Universities for ICT & business Schools in Europa, Asia, and Africa.*

Dr. Eyüp Fahri KESKENLER *Associate Professor at the Department of Materials Science and Nanotechnology Engineering, Faculty of Engineering, Recep Tayyip Erdoğan University. He received his B.Sc. and Ph.D. degrees in Physics from Physics Department, Atatürk University, Erzurum, TURKEY, in 2007 and 2012 respectively. His current research interests include semiconductor devices, renewable energy, and solid state physics applications on nano-materials.*

*We also would like to commemorate late **Prof. Hasan KARABULUT** who kindly accepted being editorial board member yet he could not see this first issue. We'll always remember his support and encouragement.*

We are aware of the fact that a quality journal can not be realized without the efforts of reviewers. They will be one of our key assets; and fast, accurate, and constructive criticism will be our key concern in reviewing process to encourage the researchers to move always forward.

Finally, we very much woud like to hear from you. Your suggestions, criticisim are most welcome in endeavour of realizing a new journal.

We hope that you would enjoy reading our very first and upcoming issues.

With our best regards…

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2- *Training Seminars for Editors and Authors by TUBITAK, May 27th, 2015, Trabzon, http://ulakbim.tubitak.gov.tr/tr/etkinliklerimiz/trabzon-egitim-programi, Last access date: 2016/12/01*

Review Article | Submit Manuscript

Turkish Journal of Electromechanics & Energy

ISSN: 2547-975X

Physical Structure, Electrical Design, Mathematical Modeling and Simulation of Solar Cells and Modules

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Received: 16 December 2015; Accepted: 08 February 2016; Published: 30 March 2016
Academic Editor: Ö. N. Cora
Turk J Electrom Energ Vol.: 1 No: 1 Page: 5-12 (2016)
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ABSTRACT In this study, the general physical structure, specifications and types of solar cells as well as their manufacturing processes, and mathematical model have been reviewed, in detail. This study is a complementary work to authors' previous study which captured considerable interest in literature. Matlab/Simulink software based simulation of Photovoltaic (PV) model has been visually programmed; and current-voltage (I-V) and power-voltage (P-V) characteristics have been obtained for different number of series and parallel connected cells at different temperature values. The simulation results have been compared with theoretical results for the modeled solar cell. Results showed that the model established is quite well in agreement with the theoretical results and it is possible to apply the model to other hybrid systems. The model can also be used as a reference by solar cell manufacturers and in the experimental studies.

Keywords: Solar cell physical structure, electrical design, Solar cell types, Solar cell manufacturing process, Photovoltaic module modeling with Matlab/Simulink.
Cite this article: M.E. Şahin, H.İ. Okumuş, Physical Structure, Electrical Design, Mathematical Modeling and Simulation of Solar Cell Modules, Turkish Journal of Electromechanics & Energy 1(1) 5-12 (2016)

1. INTRODUCTION

The continuous rise in energy demand has contribute to the increased research efforts in reneawable energy area. Especially, the improvements in solar cells have elevated to the popularity of solar energy technologies. [1, 4]. Solar cells are Photovoltaic (PV) structures that they convert solar energy to electrical energy. Solar cells convert absorbed light energy to Direct Current (DC) electrical energy. Converters are used to convert DC current to suitable AC grid electricity. Photovoltaic modules have efficiencies between %5 to %20 depending on their types [5, 7].

The efficiency of solar cells is affected by the parameters such as internal resistance, contact structure, material used, variation of temperature and light density. Therefore, the effect of different parameters should be analyzed separately using a numerical model. As far as the authors' knowledge there is no such detailed PV model in literature. Therefore, it was necessary to establish a new PV model that take necessary parameters into account [8- 12]. The model to be developed will also be useful for PV manufacturers to test their products and for researchers in experimental studies [13- 15]. In addition, it can also be used for compact systems simulation studies [16, 17].

If the literature on PV model design is reviewed, it was seen that only some of the parameters were used in PV modeling [6- 11]. Some other studies defined the PV parameters based on experimental results and focused on specific matters in PV module design. There are application-based studies in literature, as well [12- 15].

This work aimed for reviewing general physical structure, specifications and types solar cells as well as their, manufacturing processes, and mathematical models of solar cells, in detail. General mathematical model is given for solar cells including all the parameters which affect the efficiency calculation of PV systems. The PV model is programmed with Matlab/Simulink, and general I-V and P-V curves of solar cell were calculated for the different series and parallel connected cells at different temperature. The other details of these curves were given in previous studies by the authors, and mostly focused on PV module simulations and their applications [15- 18].

2. PHYSICAL STRUCTURE AND TYPES OF SOLAR CELLS

2.1. The Working Principle of Solar Cells

Sun light fall on the solar cells and it is absorbed by photovoltaic cells. In the structure of solar cells, most of the electrons are included in n-type semiconductor material while most of the electrons hole included in p-type semiconductor material. Sun light breaks electron from the n-type semiconductor material. Energizing electrons flow of p-type to the n-type semiconductor material via an external circuit. This constant and unidirectional flow of electrons forms Direct Current (DC). Electrons flowing through the founded circuit which is used for the charging of batteries or different fields return to the p-type semiconductor material. In this way, electrical energy is obtained from solar cells. The study principle of solar cells is shown in Figure 1 [25].

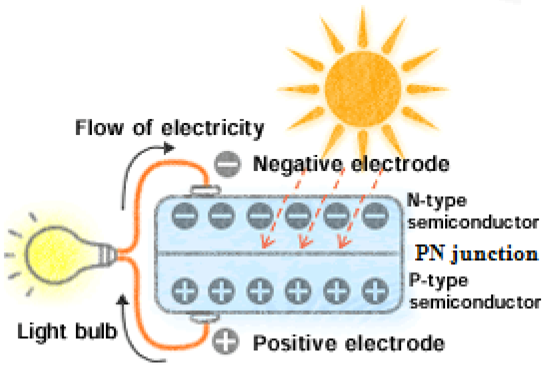


Fig. 1. The working principle of solar cells [25].

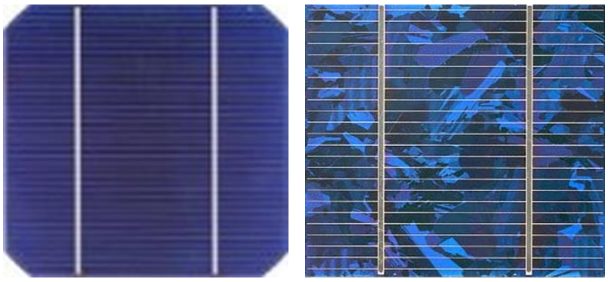
2.2. Types of Solar Cells

Solar cells (Photovoltaics) are semiconductor materials that convert sunlight directly into electricity coming to the surface. 98% of the solar cell is *Si* (silicon); and silicon is an abundant material in the earth crust. Nonetheless, impure *Si*, has generally in silicon dioxide (SiO_2, quartz) form and its purification is quite expensive. Therefore, the cost of solar panel increases.

Solar cells are generally classified as first, second and third generation. The crystalline silicon (*c-Si* and *mc-Si*) solar cells are accepted as first generation while thin film (*a-Si, CdTe, CIS* or *CIGS*) solar cells are regarded as second generation. Third generation solar cells are based on nanotechnology which are tandem, super tandem, intermediate band solar cells, etc.

The first generation (crystalline silicon) solar cells are divided into two types as Monocrystalline (*c-Si, SIN*) and Polycrystalline (*mc-Si, poly-Si*). Efficiency of monocrystalline solar cells is 15 to % 18. They are perfect for long time investments. 20% efficiency was reported in laboratory environment. The amortization period is noted between 4 to 6 years. The efficiency of this solar cell decreases to 7% after the 20 years. The pure crystal needed for these cells which make them very expensive. The cost of these type of cells is 4.5$/W, today [25]. The single monocrystalline solar cell is given in Figure 2(a).

The efficiency of polycrystalline solar cells is 12 to 15%. They do not have homogeneous crystal structures, hence they are cheaper. Maximum efficiency of 16.2% was achieved in laboratory environment for these cells. The amortization period is reported to be 2 to 5 years. The efficiency of this solar cell decreases to 14% after 20 years. The manufacturing price is cheaper than monocrystalline solar cells, and it is around 3.5$/W, currently. The single polycrystalline solar cell picture is shown in Figure 2(b).



(a) (b)

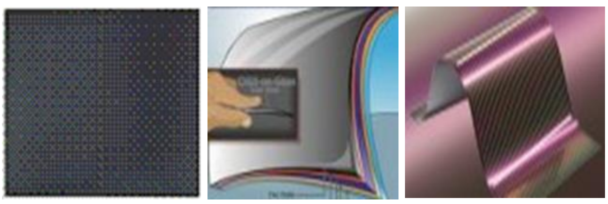
Fig. 2. Different type of solar cells; (a) Monocrystalline, (b) Polycrystalline.

The second generation (thin film) solar cells are grouped into three species as Amorphous (*a-Si*), Cadmium Telluride (*CdTe*), and Copper Indium Gallium Selenium (*CIGS*). These types of cells have 7% of solar cell market share because of their low efficiency. These fairly thin structured cells, their thicknesses vary 1 to 4 µm only, have efficiency of 7 to 14%. The manufacturing price is as low as 1$/W [25, 32].

Amorphous (a-Si) solar cells' efficiency is 8 to 10%, only. Nevertheless, its efficiency can be as high as 27% [33]. The payback time is in between 1.5 to 3.5 years. The efficiency lost of this type of solar cell is 21% during the years. The other drawback is that it needs very expensive tooling for its manufacturing.

Cadmium Telluride (*CdTe*) solar cells' efficiency is around 17% for 1 cm^2 and 11% for 8390 cm^2 surface area [33]. Manufacturing price is considerably lower compared to other types of solar cells. Two photovoltaic panels made of *CdTe* were used by University of California at Riverside to produce of hydrogen through electrolysis in 1992. This system is regarded as the first of its kind [34].

Copper Indium Gallium Selenium (*CIGS*) solar cells' efficiency is 11 to 14% [33]. It is available with the glass or flexible substrates. It has a growing market share. There are large space requirement along with the expensive manufacturing process. The species of thin film solar cells are shown in Figure 3.



(a) (b) (c)

Fig. 3. Thin film Amorphous (*a-Si*) (a), Cadmium Telluride (*CdTe*) (b), Copper Indium Gallium Selenium (*CIGS*) (c), solar cells [26].

The third generation solar cells are nanotechnology (Tandem, Super Tandem, Intermediate Band etc.) based solar cells, and those are in R&D phase. As these types of cells will have the potential of higher efficiency, it makes them very attractive and there is regarded as major breakthrough if they can be manufactured cost-effectively. Projected cost is 0.4 $ / kW [33].

For Super Tandem cells, the efficiency is 86.8% in theory and experimental efficiency of 35.4% is achieved for 1 cm^2 in literature [27, 33]. The efficiency is 63.2% for intermediate band cells in theory but experimentally is not achieved yet. Manufacturing oriented problems have not been solved yet for hot carrier cells. When those are solved, it is expected to have efficiency as high as Super Tandems.

3. MANUFACTURING PROCESS OF SOLAR CELLS

Solar cells are manufactured from ingots having silicon crystal with 99% purity after processing the sea sand. Then the material is made suitable for electrical conduction with a metal coating, via scribing and slicing into thin plates. The obtained solar cells are then formed and modules are manufactured. These modules form a photovoltaic system and those are combined with required converters and transmitted to the network. The main steps of manufacturing process are summarized in Figure 4 [26, 27].

Fig. 4. The main manufacturing steps of solar cells.

By melting the silicon quartz is obtained. The obtained product has 98% pure of silicon which also includes metals such as aluminum, iron [26]. This silicon is converted into polycrystalline structure with electronic rating called Siemens method and gains 99.99% purity. Silgrain material is used in this process. Silgrain is reacted with hydrochloric acid in the specific ratio of copper catalyst.

Ingot is the name given to the semiconductor material in solid state. It can be in mono or polycrystalline form. A mono crystal ingot is obtained by pulling the crystal from the silicon melt. The process is named after Polish scientist Jan Czochralski who invented the method in 1916 while investigating the crystallization rates of metals [28]. The polycrystalline ingot is melted in a vessel and is obtained by repeated freezing in another vessel. The manufacturing process is relatively easy, however; the efficiency is low. The most common methods for manufacturing multi-crystalline ingots are the silicon casting and the Bridgeman method. These two methods are shown in Figure 5. Silicon casting (Figure 5.a) can be carried out in a separate crucible after silicon is poured into it from a melting crucible, as indicated. In contrast, using the Bridgeman method (b), the silicon can be melted and directionally solidified in the same crucible. This technique is referred as directional solidification [29].

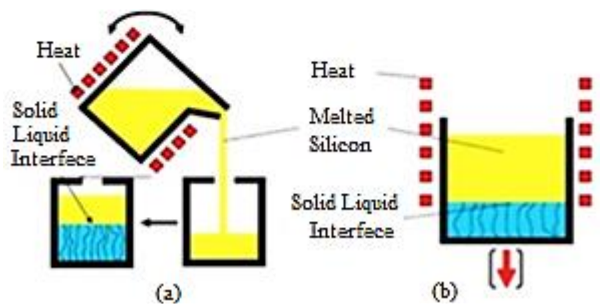


Fig. 5. Silicon casting (a), Bridgeman methods (b) for manufacturing multi- crystalline ingots.

In the slicing stage the silicon is divided into thin slices called "wafers". Nevertheless, it is not enough a raw material to make solar cells. The multi-crystalline silicon ingot is cut by a wire saw into the blocks. These blocks are then cut by a wire saw into wafers. During this process the surface is repeatedly cleaned and is refined. The processing of square instead of circular solar cells into solar modules will increase the utilization of the available module area. Then, the resulting wafers have a thickness between 160 and 220 µm. The sawing of the ingot incurs an amount of 50 percent of material sacrifice. The slicing process is shown in Figure 6.

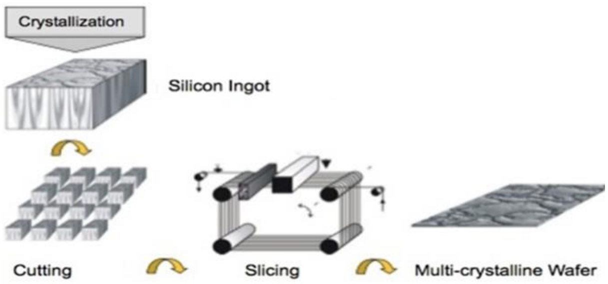


Fig. 6. The slicing process of the ingots [24].

Plate area of mono or polycrystalline of solar cells is usually125mm×125mm or 156mm×156mm and the thickness is in the range of 160-220 µm for the starting material. The next step is restoring the defects, cleaning the surface and phosphorus diffusion (POCL) process. While the front of the panel is selected generally as doped (adding impurities to) region by the minority carriers, back side of the panel is selected doped by the majority carriers. Phosphorus diffusion is used for n-type contact. Aluminum boron alloy is useful to increase the creation of very thin p-type contact and light absorption surface [24, 30]. The next stage is isolation of edges and addition of anti-reflection layer. In the process step of metallization, electric contacts are printed on the solar cell (both front and back side). This process is shown in Figure 7. After baking the electric contacts in an oven, the next step is the electrical power and optical quality is measured and the cells are classified accordingly.

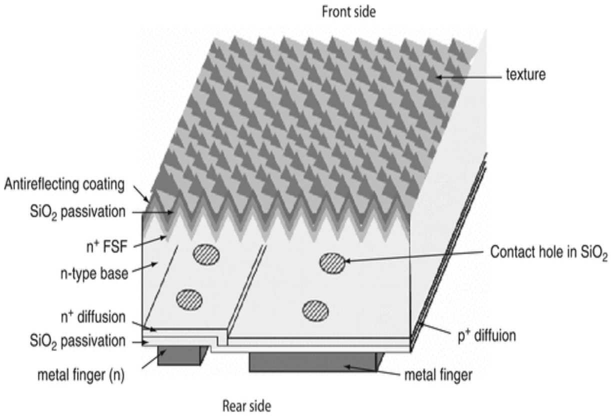


Fig. 7. Diffusion and metallization process made of cell section [30].

In order to obtain the appropriate voltages and outputs for different applications, single solar cells are interconnected to form larger units. Cells connected in series have a higher voltage, while those connected in parallel produce more electric current. Cells connection is shown in Figure 8.


Fig. 8. Photovoltaic cells module connection.

The interconnected solar cells are usually embedded in transparent Ethyl-Vinyl-Acetate, fitted with an aluminum or stainless steel frame and covered with transparent glass on the front side. This process is called lamination process. The lamination process of PV panel is shown in Figure 9.

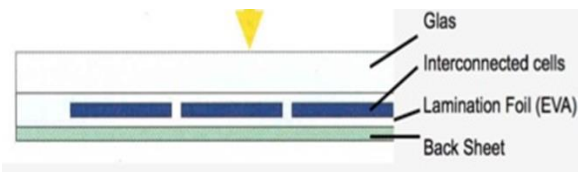


Fig. 9. The lamination process of photovoltaic panels.

In addition, a PV-system consists of multiple components, including cells, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output. The electrical specifications of solar cells and PV module design using mathematical equations will be viewed in the next step.

4. ELECTRICAL SPECIFICATIONS OF SOLAR CELLS

Solar cells are based on the Shockley diode equation in Equation 1, electrically. However, with the other general solar cell parameters the equality is given as an Equation 2.

$$I = I_0\left[\exp\left(\frac{qV}{kT}-1\right)\right] \tag{1}$$

$$I = I_L - I_0\left[\exp\left(\frac{q(V+R_s.I)}{n.k.T}\right)-1\right]-\frac{V+R_s.I}{R_{sh}} \tag{2}$$

Solar cell voltage is obtained by neglecting the series shunt resistor;

$$V = \frac{n.k.T}{q}\ln\left[\frac{I_L+I_0-I}{I_0}\right]-R_s.I \tag{3}$$

Here, ideals factor (n), series resistance (R_s) and shunt resistor (R_{sh}) are the parameters which vary depending on the characteristics of the solar cell. Other parameters are; the Boltzmann constant (k), the electron charge (q) and the temperature of the solar cell (T).

Equivalent circuit model of the solar cells was proposed in 1994 by Lorenzo [11]. This model consists of a current source and a diode connected in parallel. The series resistance (R_s) represents the internal losses caused by the current flow of the solar cell. Connected parallel diodes resistance (R_{sh}) represents the leakage current taken place from the losses occurring in soil. It is often neglected as it is comparatively small with respect current produced. General equivalent circuit model of the solar cell is given in Figure 10.

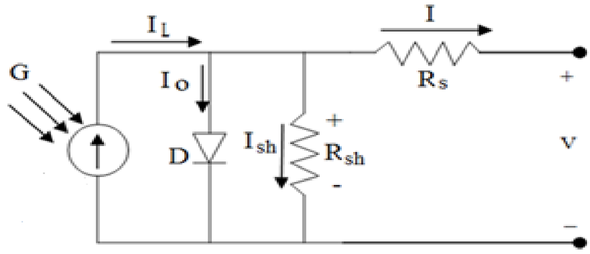


Fig. 10. General equivalent circuit model of the solar cell.

The power given to the load, only depends on the resistance. If the R load is very small, solar cell works on M-N line as a current source near the short circuit current as illustrated in Figure 11. If the R load is very big, solar cell works on P-S curve as a voltage source near the open circuit voltage. The point A is the Maximum Power Point (MPP).

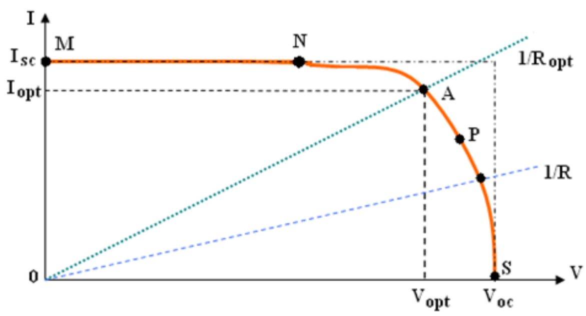


Fig. 11. Current-Voltage *(I-V)* characteristic of solar cell.

The other parameters affect the *I-V* curves are sunshine and temperature. The solar cell current is dependent on cellular operating temperature (T) and the absorption of sunlight (G) which is given in Equation 4. The amount of sunlight energy absorbed by the sun is G, and intensity ranges from 0 to 1100 W/m^2. The temperature coefficient, K_i, is depended to the short-circuit current. Overall 3 mA/ºC constant value is received [9]. The effect of sunshine and temperature variations on *I-V* curves are shown in Figure 12. Depending on the light intensity, current (I_{SC}) and voltage (V_{oc}) increases or decreases, however; temperature increase reduces the voltage (V_{oc}) while the current (I_{SC}) slightly increases.

$$I_L = \left[I_{sc} + K_I (T - T_{ref}) \right] .G \quad (4)$$

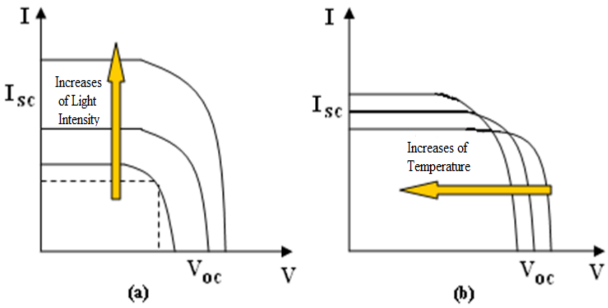


Fig. 12. Sunshine (a) and temperature (b) variations how to effect *I-V* curves.

5. EQUIVALENT CIRCUIT OF SOLAR CELL MODULE AND MODELING

A simple solar cell can have a maximum of 0.5 V at 2 W powers. Thus, the desired voltage and current can be obtained by connecting the cells either in series and parallel. The resulting structures are referred as solar cell modules. The number of series cells is taken as N_S and parallel cells are taken as N_p in equivalent circuit model. The PV module structure and equivalent circuit model is shown in Figure 13 (a) and (b).

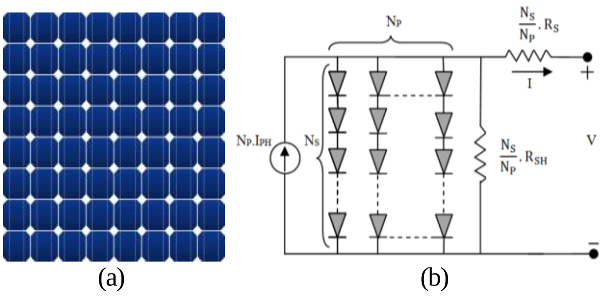


Fig. 13. (a) PV module structure, (b) Equivalent circuit model.

Increasing the number of serial cells increases voltage and increasing the number of parallel cells increases current as a characteristic of solar module. This situation is shown in *I-V* curves given in Figure 14. The general current of the PV module in which serial resistance (R_S) is neglected, is shown in Equation 5.

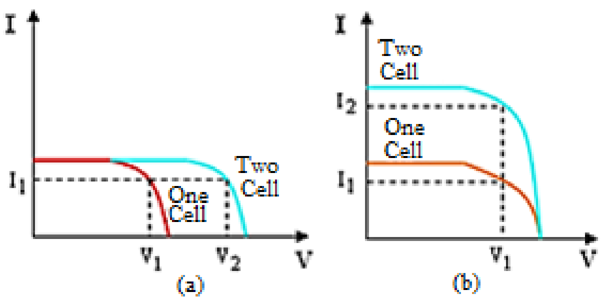


Fig. 14. *I-V* curves for series (a), parallel (b) connected cells.

$$I = N_P.I_{PH} - N_P.I_0 \left[\exp(q.\left(\frac{V}{N_S} + \frac{I.R_S}{N_P} \right) / k.T_C.A) - 1 \right] \quad (5)$$

Voltage equation can be derived from the PV module current equation and solar cells current Equation 4 which depends on *T* and *G*, embedded in it. Final form of the equation can be written as in Equation 6. The details of these equations are given in previous studies [18, 23].

$$V_{PV} = \frac{N_S.n.k.T}{q} \ln \left[\frac{(I_{SC} + K_I (T - T_{ref})).G + I_0 - I_{PV} + N_P}{I_0.N_P} \right] - \frac{N_S}{N_P}.R_s.I_{PV} \quad (6)$$

Using Equation 6, the solar cells module is programmed visually with the Matlab/Simulink software as it can be seen in Figure 15.

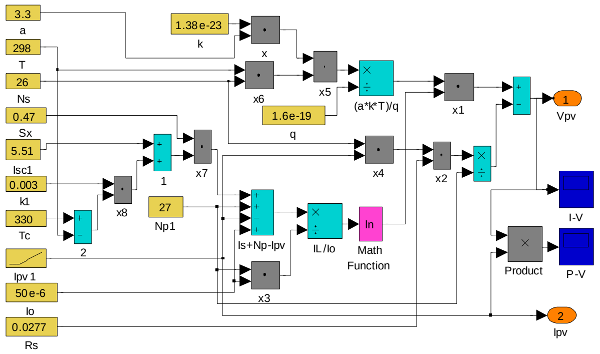


Fig.15. Matlab/Simulink equivalent model of the solar cells module.

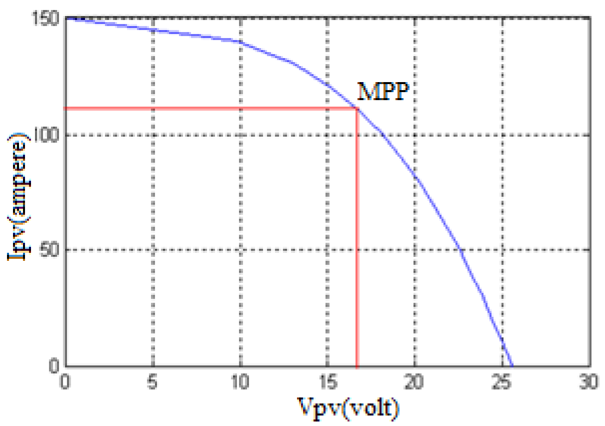
Using the equivalent model of solar cells module in Figure 14, the simulations were performed. Constant and variable parameters used in these simulations are given in Table 1. This model needs some more electrical components to be used as an electrical source for circuit's simulations [18, 23].

Table 1. Constant and variable parameters used in the simulations.

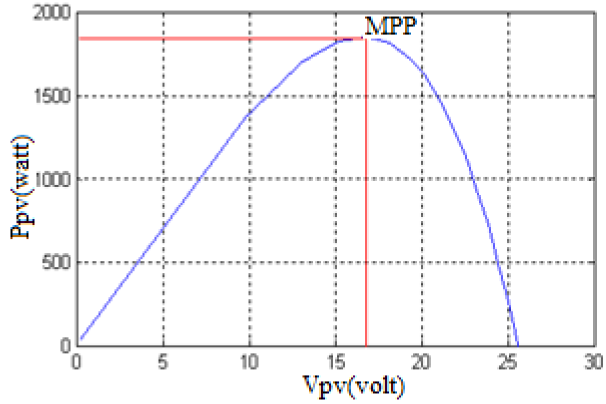
Constant Accepted Parameters	Values
Boltzmann constant (*k*)	1.38x10-23J/K
Electron charge (*q*)	1.6x10-19 C
Reference temperature (*T*)	(273+25) K
Short circuit current temperature constant (K_I)	3mA/ºC
Diode current (I_o)	50µA
Short circuit current (I_{sc})	3.92A
Variable Accepted Parameters	**Values**
The number of series cells (N_s)	105
The number of parallel cells (N_p)	148
Series internal resistance (R_s)	0.0277Ω
Variable temperature (T_x)	0-100ºC
The light absorption (S_x=*G*)	0.1-1kW/m²
Ideality factor (*a*=*n*)	1.2-5

6. SIMULATION RESULTS FOR SOLAR CELL MODULE

The solar cell modules current-voltage (I-V) and power-voltage (P-V) characteristics were obtained as in Figure 16 using the simulations of solar cell modules and the parameters given in Table 1. The maximum power point is around 1800 Watts for 17V.



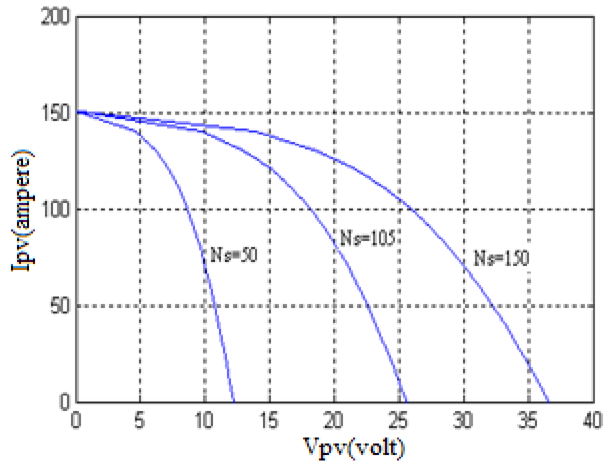
(a)



(b)

Fig. 16. The solar cell modules (a) current-voltage (I-V) and (b) power-voltage (P-V) characteristics.

Figure 17 (a) and (b) show how the solar cells module current- voltage (I-V) characteristics vary for different number of cells connected in serial and parallel. As the number of serial connected solar cell increases, the open circuit voltage increases and the short circuit current remains same. Likewise, as the number of parallel connected solar cell increases, the short circuit current increases and open circuit voltage remains same.



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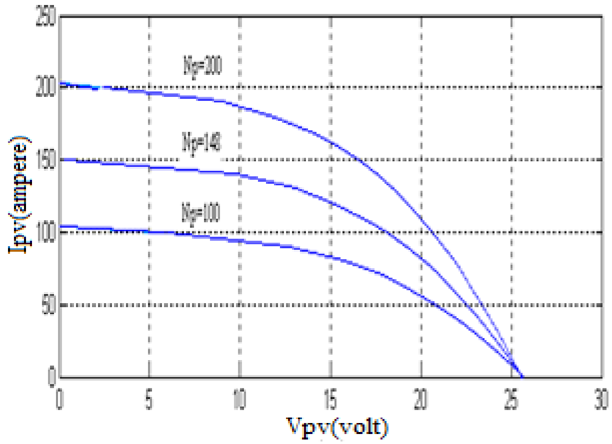
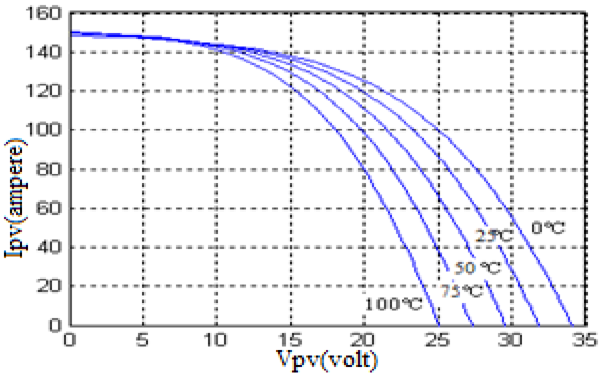


(b)

Fig. 17. Current-voltage variation characteristics of for different cell numbers of solar modules connected in (a), series and (b) parallel.

Figure 18.a and b show (I-V) and (P-V) curves at different temperatures for the solar cell. In Figure 18 (a), open circuit voltage of the solar cell temperature is decreased (V_{oc}), but short circuit current value (I_{sc}) is increased in a small amount. However, as shown in Figure 18 (b), the maximum power point decreases with temperature increase. From 0 °C to 100 °C maximum power point changes from 2600 W to 1800 W, approximately. This shows the efficiency decreases in solar cells depending on temperature. This is in well agreement with the theoretical calculations.



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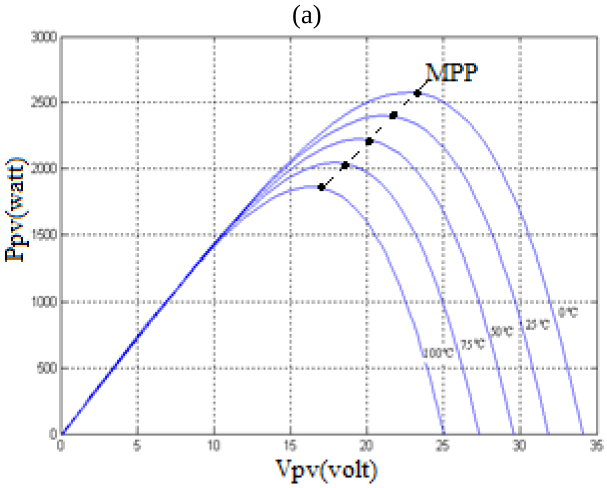

(b)

Fig. 18. a) Current-Voltage (I-V), b) Power-Voltage (P, V) for different temperature values (from T = 0 ° to T = 100 ° C).

These results show only the variation of (I-V) and (P-V) curves for different numbers of serial and parallel connected cells with respect to temperature. Effect of other parameters was examined in a detail by the authors in a previous study [18].

7. CONCLUSION

General structure, specifications types as well as manufacturing processes and mathematical model of solar cells have been reviewed, in detail in this study, the solar cell of the resulting mathematical model is visually programmed with the Matlab/Simulink software and the solar cell module was simulated. The obtained simulation results were found to be quite well agreement with ideal PV sources known in theory. It is noted that the modeled solar cells can be used in combination with other electrical systems.

Acknowledgement
This study was supported through The Scientific & Technological Research Council of Turkey (TUBITAK) project # 111E292.

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Turkish Journal of Electromechanics & Energy

ISSN: 2547-975X

A Flexible Alternating Current Transmission System-Green Plug Scheme for Smart Grid Applications

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Received: 13 July 2015; Accepted: 03 March 2016; Published: 30 March 2016
Turk J Electrom Energ Vol.: 1 No: 1 Page: 13-20 (2016)
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ABSTRACT: *The paper presents a new dynamic voltage stabilization Flexible AC Transmission System (FACTS) scheme for smart- grid applications with nonlinear loads and distributed generation. The use of wind, photovoltaic and battery storage systems with nonlinear loads and DC-AC solid state interface creates voltage stability and power quality problems and reduce energy efficient utilization. In this paper, a Green Plug Shunt Filter Compensator (GP-SFC) is validated as an effective FACTS-switched shunt LC compensation device for dynamically modulating the Thevenin's impedance at the point of common coupling for efficient energy transfer utilization as well as voltage stabilization. The GP-SFC FACTS device is validated using MATLAB-Simulink simulation environment at varying load and system conditions including open circuit, short circuit fault conditions, and load reductions. The coordinated, multi-regulation, inter coupled dynamic controller scheme ensures the GP-SFC device effectiveness in improving power quality at key AC buses, while reducing inrush currents and transient over-voltage/switching recovery voltage excursions.*

Keywords: Smart grid, Shunt filter compensator, Energy efficiency, Power quality enhancement.

Cite this article: *A. M. Sharaf, F. H. Gandoman, A. Rahimi, A Flexible Alternating Current Transmission System-Green Plug Scheme for Smart Grid Applications, Turkish Journal of Electromechanics & Energy 1(1) 13-20 (2016)*

1. INTRODUCTION

Power quality issues and reliability, security and voltage stability problems are new issues in electric utilities and emerging smart-grid systems. The increasing use of photovoltaic cell (PV) and wind farm and other distributed generation (DG) renewable energy resources have changed the reliability, security and power quality of the electrical systems remarkably [1, 2]. Fast controllable FACTS devices are considered as effective solutions for long and short duration voltage changes, voltage imbalances, waveform distortion, voltage fluctuation and power frequency of modern electrical networks that lead to improving power quality [3, 4].

In order to reduce feeder active and reactive power losses as well as to enhance recovery dynamic response on the electrical system after open, short circuit operations and load changing and modulated capacitor banks have been widely used in modern electrical system [5, 6]. Fixed power filters which are low-cost, simple, and robust structures are usually installed in industrial utilization networks to improve the power quality. Nonetheless, the fixed parameter power filters and capacitor banks are limited in effectiveness for dynamic type of loads and may result in resonance in some cases [7, 8].

In this paper a new Green Plug-Shunt Filter Compensator (GP-SFC) device is validated using Matlab-Simulink software environment with a new tri-regulation multi loop error driven controller for voltage stabilization, energy efficiency and secure delivery to the load. The new GP-SFC utilized an IGBT/GTO switch controlled by the dynamic error driven control strategies using a multi-loop dynamic error driven. Also, it is coordinated a regulation, control scheme and a Weighted–Modified fast to act PID (WMPID) controller.

The current manuscript is organized as follows: The FACTS scheme is described in Section 2. In Section 3, working principle of the system is explained. Finally, Sections 4 and 5 present the Matlab/Simulink digital simulation results under fault open circuit, short circuit and load varying conditions, and conclusions, respectively.

2. THE FACTS GREEN PLUG-SWITCHED FILTER COMPENSATOR

2.1. GP-SFC Scheme

The proposed GP-SFC dynamic voltage stabilization device is a member of modulated switched/modulated power filters and switched capacitor compensators family [9-15].

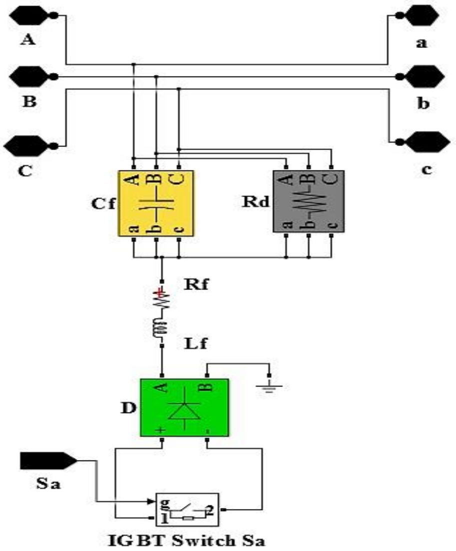


Fig. 1. GP-SFC device configuration

proposed GP-SFC a switching modes of operation using a tuned arm filter has been controlled solid state switch *(Sa)*. The configuration of the proposed GP-SFC is shown in Figure 1.

2.2. The Multi Regulation Controller

One of most important parts of FACTS devices is controller as it plays a crucial role to auxiliary the other devices in order to improve the power quality. The dynamic error driven tri-regulation controller of the proposed GP-SFC is given in Figure 2. It is based on measurement of the current I_{rms} at the source point. The current error signal is obtained by comparing the measured I_{rms} current against a reference current, I_{rms_ref}. The angle delta is used in the PWM generator as the phase angle of the sinusoidal control signal. The switching frequency used in the sinusoidal Pulse Width Modulation (PWM) generator is $f_{s/w}$ - 1250 Hz. Moreover, the global output signal from the dynamic error driven controller is followed by a WMPID controller is displayed in Figure 3. WMPID includes an error sequential activation supplementary loop, ensuring fast dynamic response and effective damping of large excursions, in addition to the conventional PID structure.

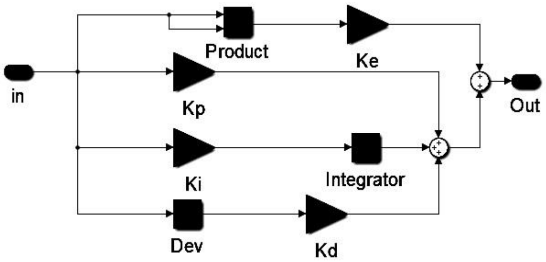


Fig. 3. Weighted-modified PID controller with error-squared loop.

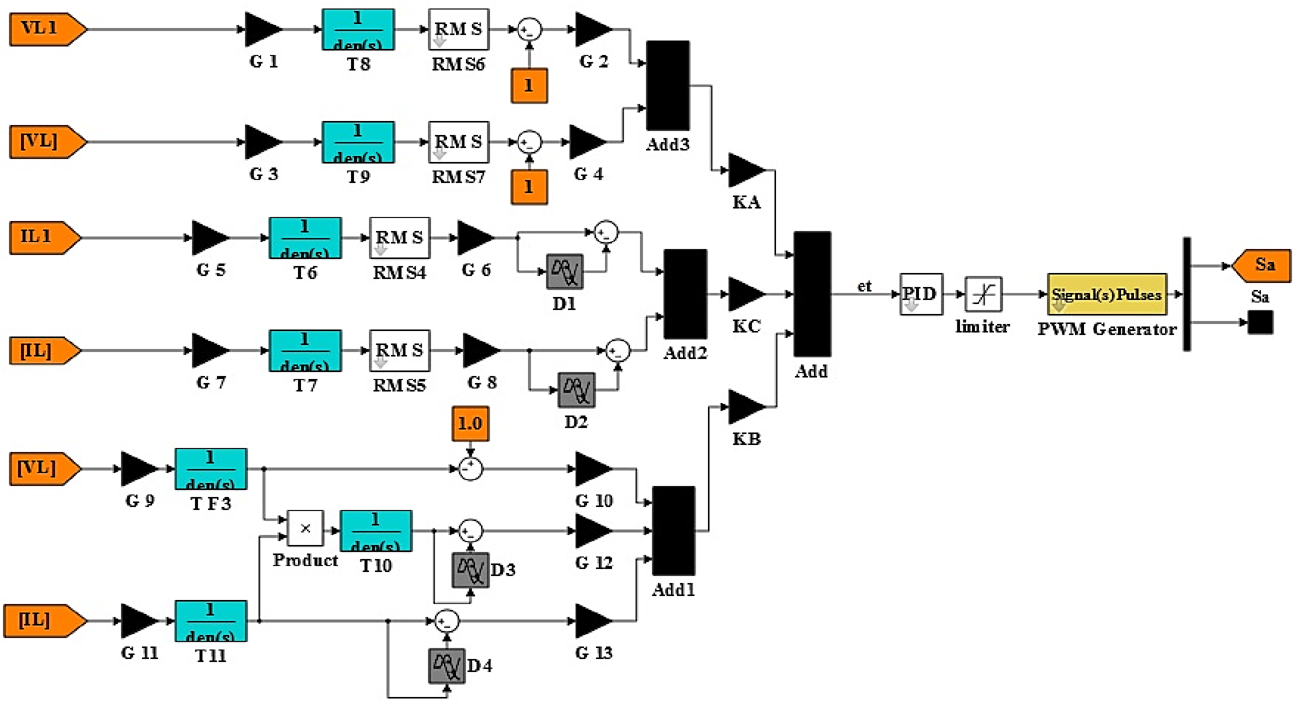


Figure. 2. Dynamic error driven Tri-regulation controller.

3. AN AC SYSTEM CASE STUDY

An AC system case study with additional FACTS GP-SFC is shown in Figure 4. The case study is comprises a local hybrid load (linear, nonlinear and induction motor type loads) and is connected to the infinite bus with 138kV, substation bus through 8 km feeder. In this paper, a nonlinear load has been designed in MATLAB-Simulink in order to study behavior of nonlinear load under different circumstances (Figure 4). The unified AC system, GP-SFC and the dynamic control parameters are given in the Appendices *A* and *B*.

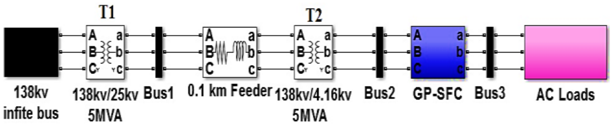
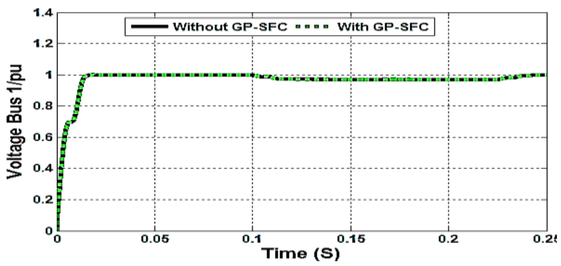


Fig. 4. The AC system case study.

4. DIGITAL SIMULATION RESULTS

4.1. Short Circuit Condition

The Matlab-Simulink Software environment was utilized to validate the effectiveness of the GP-SFC scheme of the host smart grid under short circuit (SC) condition. In addition, a three-phase short circuit in load bus is applied at time 0.02s of the AC grid, and it is cleared after 0.02s. The results of the simulation under short circuit condition in bus 1 and bus 2 are given in Figure 5. Based on the results obtained, the GP-SFC scheme was validated to be effective in stabilizing bus voltages, improving power factor and reducing inrush currents under short circuit faults.



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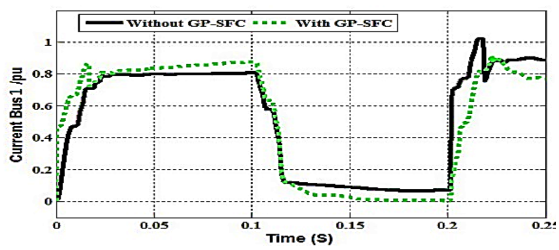

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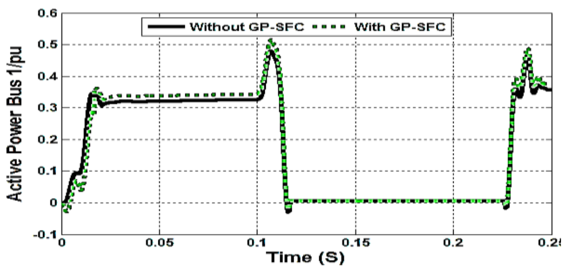

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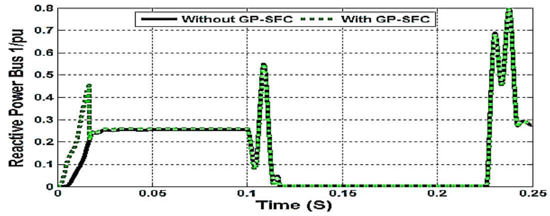

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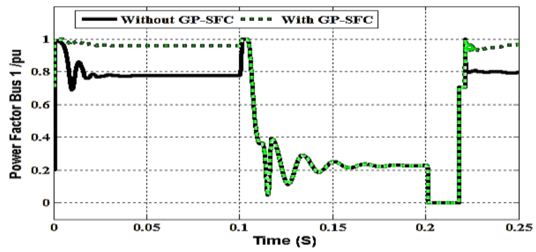

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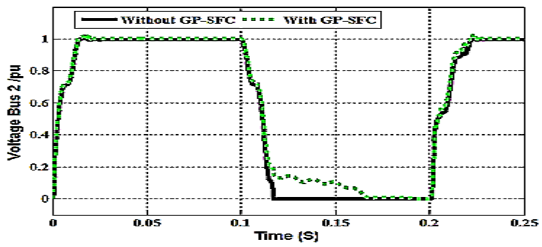

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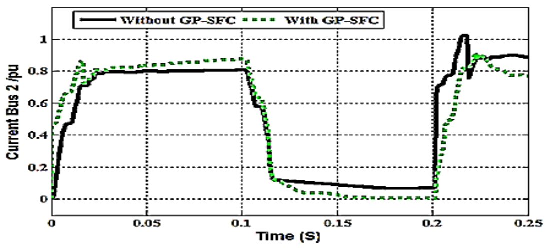

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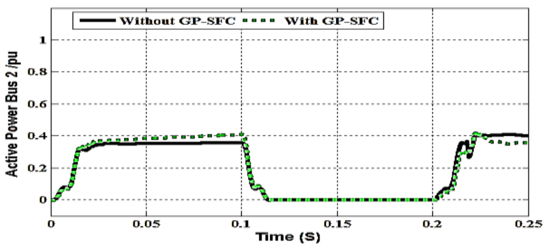

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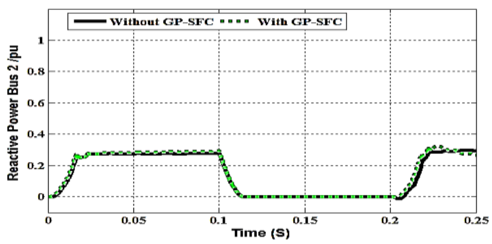

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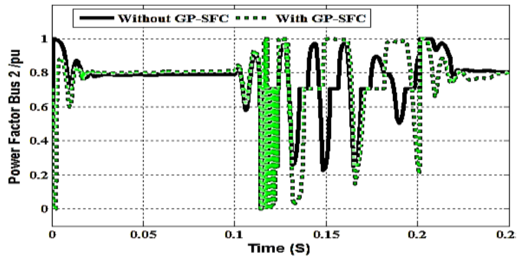
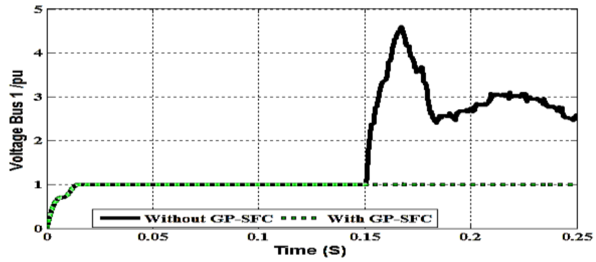


(j)

Fig. 5. (a) RMS voltage waveform in bus 1, (b) RMS current waveform in bus 1, (c) Active power waveform in bus 1, (d) Reactive power waveform in bus 1, (e) Power factor waveform in bus 1, (f) RMS voltage waveform in bus 2, (g) RMS current waveform in bus 1, (h) Active power waveform in bus 2, (i) Reactive power waveform in bus 2, (j) Power factor waveform in bus 2, all under short circuit operation.

4.2. Open circuit

In this section of the paper, an open circuit is occurred near to load and changing of key parameter shown in Figure 6. Additionally, as it can be seen, dynamic response and power quality in buses 1 and 2 have been improved. Also, the power factor during open circuit fault with GP-SFC in key buses has insignificant fluctuation, especially in bus 1.



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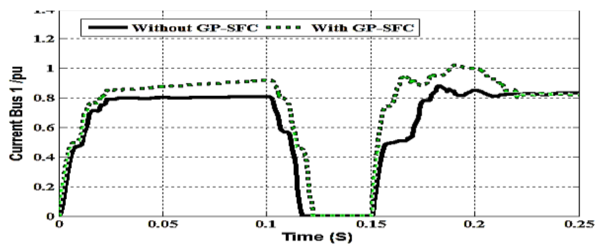

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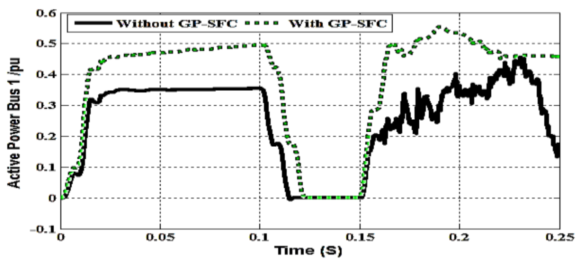

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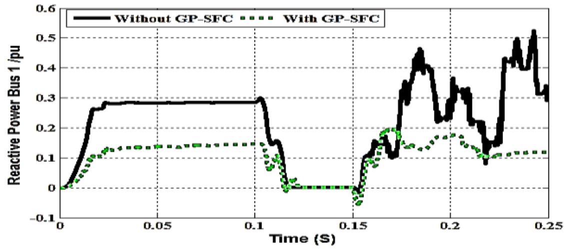

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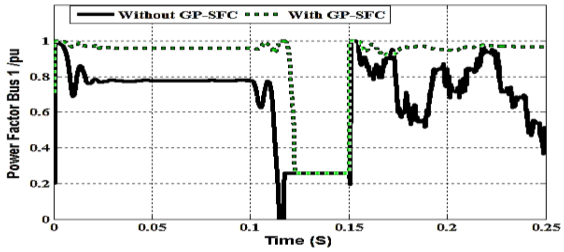

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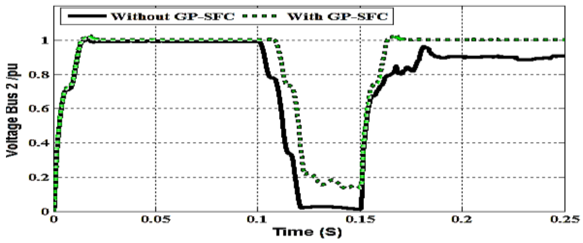

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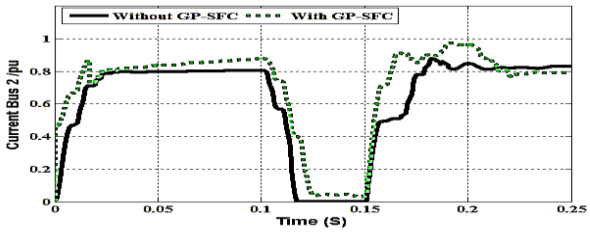
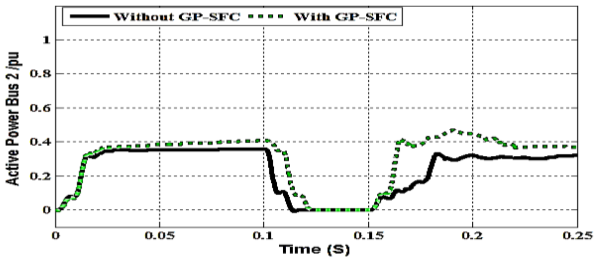


(g)



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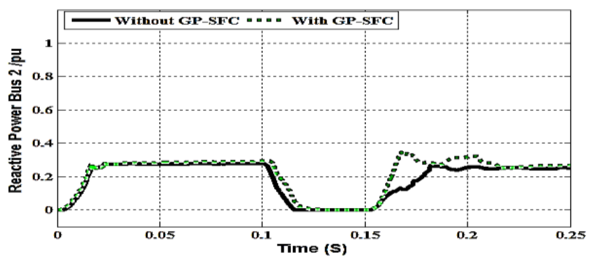
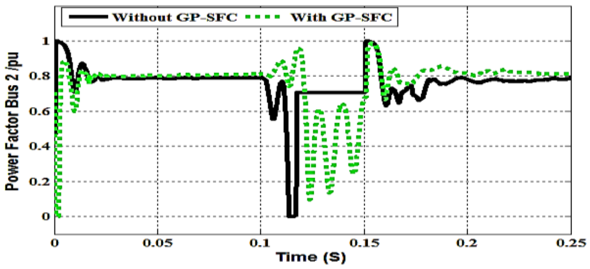


(i)

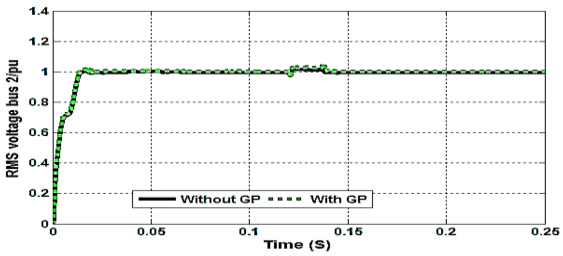


(j)

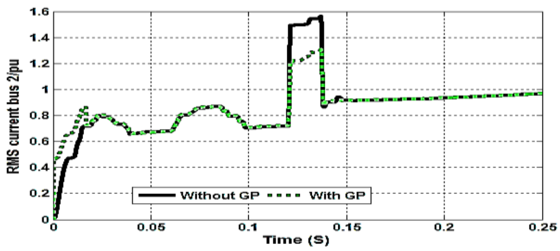
Fig. 6. (a) RMS voltage waveform in bus 1, (b) RMS current waveform in bus 1, (c) Active power waveform in bus 1, (d) Reactive power waveform in bus 1, (e) Power factor waveform in bus 1, (f) RMS voltage waveform in bus 2, (g) RMS current waveform in bus 1, (h) Active power waveform in bus 2, (i) Reactive power waveform in bus 2, (j) Power factor waveform in bus 2, all under open circuit operation.

4.3. Hybrid Electric-Load Variations

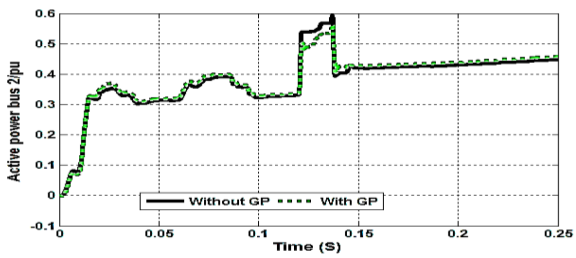
In order to examine the AC grid response to load excursions in the presence of the GP-SFC and without FACTS-GP, following conditions are dictated to the grid. At 0.02s, linear load is disconnected and then reconnected after 0.04s. At 0.1s, nonlinear load is disconnected and reconnected after 0.04s. At 0.18s, motor load's torque decreases by 50% for the period of 0.04s. At 0.22s, motor's torque increased by 50% for the duration of 0.04s. Figure 7 show the results obtained for load variation condition with and without GP-SFC in the case study.



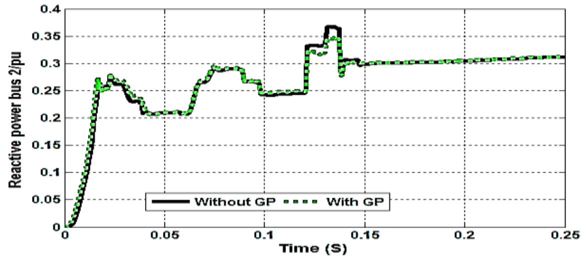
(a)



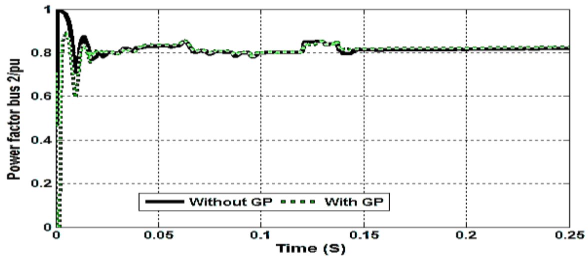
(b)



(c)



(d)

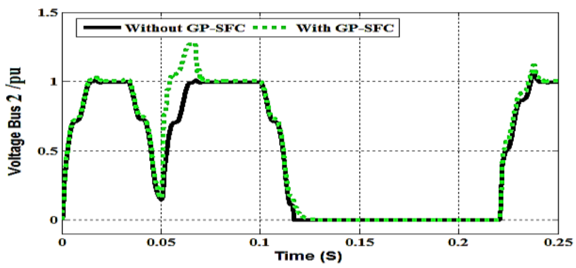


(e)

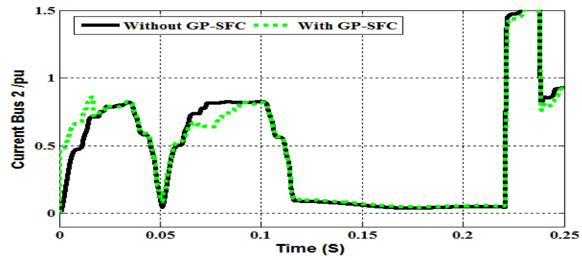
Fig. 7. (a) RMS voltage waveform in load bus, (b) RMS current waveform in load bus, (c) Active power waveform in load bus, (d) Reactive power waveform in load bus, (e) Power factor waveform in load bus, all under load variation operation.

4.4. Short and Open Circuit Condition

In order to show flexible performance of proposed GP-SFC, two different types of faults at same time has been analyzed in the case study. First, an open circuit is occurred near to load with 20ms duration time in 0.05s to 0.07s. After that, a short circuit is occurred near to load with 120ms duration time in 1s to 2.2s. The simulation results of case study with and without GP-SFC in load bus are shown in Figure 8.



(a)



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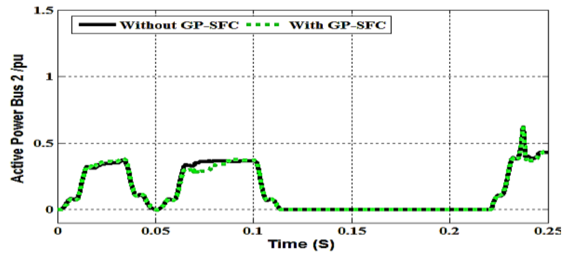

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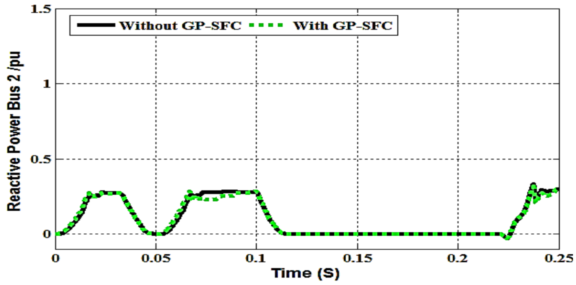

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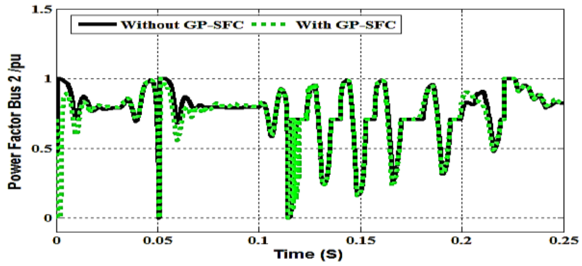


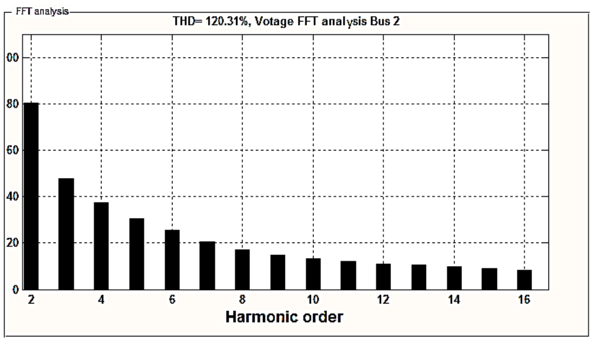
(e)

Fig. 8. (a) RMS voltage waveform in load bus, (b) RMS current waveform in load bus, (c) Active power waveform in load bus, (d) Reactive power waveform in load bus, (e) Power factor waveform in load bus, all under open and short circuit operation.

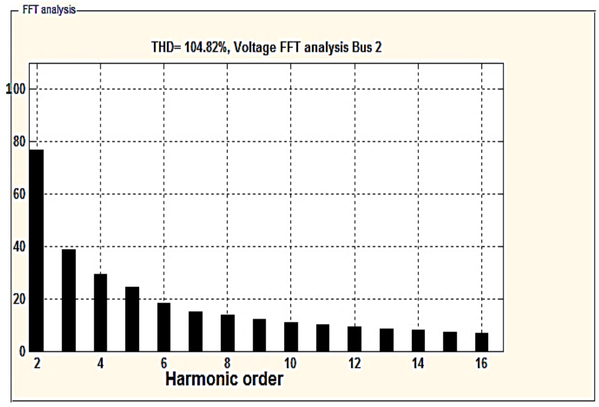
4.5. Power Quality Enhancement

The total harmonic distortion (THD) is an important feature of merit used to quantify the level of harmonics in voltage or current waveforms. In this section, the harmonics of the load bus of current and voltage are analyzed.

Figure 10 show voltage, and current of the THD of the load bus without FCTS-GP as a function of time, respectively. For constant series compensation, as seen in Figures 9(a) and 9(b), the rate of THD has been increased (by percentage) due to using nonlinear load on power system, however; as seen in Figure 9(c) and 9(d), utilizing the FACTS-GP, the THD of the line current terminal voltage in load bus is improved.



(a)



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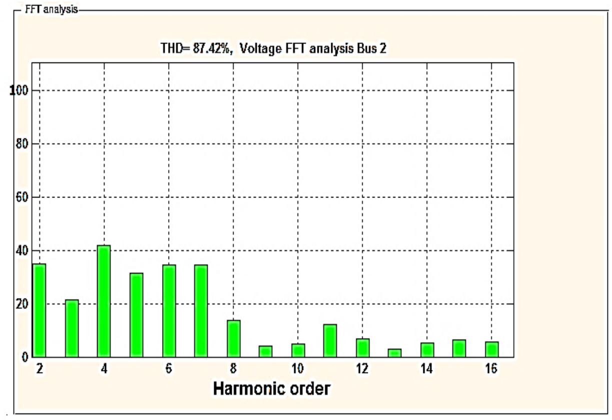
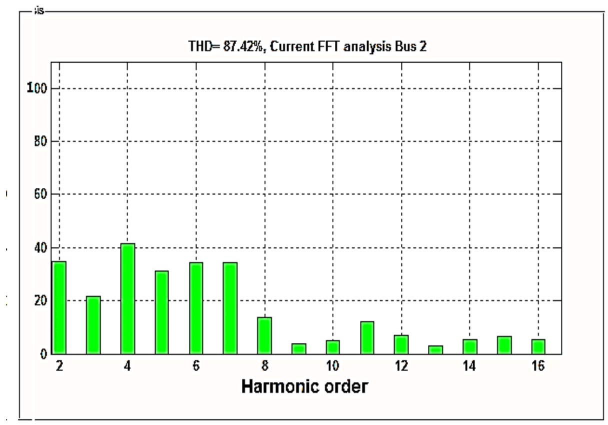


(c)



(d)

Figure. 9. (a) FFT analysis of voltage at load Bus 2 without GP-SFC for load changing operation, (b) FFT analysis of current at load Bus 2 without GP-SFC for load changing operation, (c) FFT analysis of voltage at load Bus 2 with GP-SFC for load changing operation, (d) FFT analysis of current load Bus 2 with GP-SFC for load changing operation.

5. CONCLUSIONS

This paper presents a FACTS switched/modulated scheme (GP-SFC) to use in smart grid distribution systems. The GP-SFC is effective in dynamic voltage stabilization at load AC bus and in limiting dynamic transient recovery voltages and inrush current conditions. A tri-regulator coordinated error driven, is utilized to adjust the sinusoidal PWM switching patterns for the solid state switching to ensure fast dynamic bus voltage stabilization and power factor correction. The same GP-SFC topology can be utilized with different modified control strategies for hybrid DC-AC interface schemes using DG and renewable PV/Tidal/Wave/Wind/Micro-Hydro/Fuel Cell green energy and storage systems. The digital simulation results validated the dynamic fast response and stabilization effectiveness of the proposed FACTS GP-SFC scheme for improving voltage regulation, limiting inrush current conditions, and modifying power factor.

Appendix

A) Case study parameters

Transmission Line	25 kV (L-L), 8 km	
	R/Km=0. 35 Ω, L/Km=0.4 mh	
Infinite Bus	138 kV, X/R=10	
FACT-GP	Csh=275µf	
	Rf=0.15Ω, Lf=3mh	
Local Hybrid Ac Load	Induction Motor	0.2 MW, 4 Poles
		Rs=0.01965pu, Ls=0.0397 Pu
		Rr=0.01909pu, Lr=0.0397 Pu
		Lm=1.354 Pu
	Linear Load	P=1.8 Mw,Q=0.43Mvar
	Nonlinear Load	P=0.9 Mw,Q=0.43Mvar
Power Transformer	T1	138/25kV, 5 MW
	T2	25/4.16kV, 5 MW

B) Controller system parameters

Device	Value
GP-SFC Controller Gains	Ke=1, Kp=25, Ki=2, Kd=1, PWM Frequency Fs=1750 Hz

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