# Assessment of Sudden Voltage Changes and Flickering for a Grid-Connected Photovoltaic Plant

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**Abstract-** In this paper, sudden voltage changes studies are carried out for a 20 MW grid-connected photovoltaic plant to assess the impact of energization of the step-up transformers, which may cause a voltage dip that could be a nuisance to the point of common coupling (PCC) of the transmission system. In addition, the flicking performance of the plant is checked. At the design stage, these studies are necessary to verifying compliance of a planned photovoltaic plant according to the regulatory grid codes and international standards by designing its grid connection. Based on the study results, the main breaker which is connected to the PCC should be ordered with 150 Ohm Pre-Insertion Resistor to make the photovoltaic plant comply with grid code requirements of sudden voltage changes. The plant is compliant with the FICHTNER standard for long-term flicker severity and with the short-term flicker severity requirements of Engineering Standard P28.

**Keywords-** Grid Codes, Grid-Connected Photovoltaic Plants, Energization, Flickering.

## 1. Introduction

Recently due to lack of fuels and environmental pollution produced by greenhouse gasses, renewable resources have widely used. The wind energy and solar energy play a significant role in the current situation. However, the interconnection of large photovoltaic plants to the power grid may cause problems concerning the stability and safety of the utility grid, as well as power quality problems. Likewise, the solar irradiation variations may source power oscillation and voltage flicker. Therefore, the interconnection of these projects with variable generators to the power system is a challenge both for the transmission system operator and the producers of the projects [1]-[3]. Also, the technical requirements from both the utility power system grid side and the photovoltaic system side need to be satisfied to guarantee the safety of photovoltaic installer and the reliability of utility grid [3], [4].

These challenges led transmission system operators to oblige the grid impact studies (GIS) to limit the problems that maybe appear in the grid from this penetration. GIS are necessary to plan the photovoltaic plant interconnection at the design stage and verify the plant compliance with governing standards. The current work is part of GIS for a grid-connect photovoltaic plant which is one of the outgoing renewable energy projects in Jordan. KAYAN Power Systems Solutions Ltd has been invited to conduct this GIS. Grid interconnection of photovoltaic plants is accomplished through the inverter, which links between DC photovoltaic modules and AC system. Inverter system is consequently very significant for grid-connected photovoltaic systems [3], [5]. The design and controllers of inverters and cables layout have been provided by the plant manufactures to get more accurate simulation results of the planned plant. Hence this enables the transmission system operator and the plant planner to take the proper actions and design. In addition, these results could get the guidance to the transmission system operator to approve compliance of the photovoltaic plant with the grid codes requirements and also approve the final design of the plant from the manufacturers.

The grid code requirements for photovoltaic plants was prepared to provide guidance for the assessment of the impact of fluctuating loads on the quality of supply seen by other customers connected to the same part of the network. The aim of this study is to show the dynamic effects of the energization of a single 3.15 MVA, three winding unit transformer on the plant, and then to show how many transformers are able to be energized simultaneously without exceeding the grid requirements. The dynamic effects of the transformer energization were studied under normal network operating conditions to calculate sudden voltage changes (voltage step changes) at the point of common coupling (PCC). The PCC is the 33kV bus bar as defined by the Jordanian grid code compliance for photovoltaic plants connected to the medium voltage [6], [7].

## 2. Implemented System Modelling

The components data of the photovoltaic plant, transmission grid, and configurations, and used conditions in this paper were taken from the manufacturers of photovoltaic and from the utility to ensure more practical considerations. Consequently, the results lead to respectable actions and arrangements to comply the photovoltaic plant operation with the grid code. As the design stage is not completed and information has not been provided, so acceptable and feasible assumptions have been made based on previous experience and typical values that provide the actual performance of the plant as of now.

The considered photovoltaic plant is a gird-connected plant. The plant consists of 18 x 1.56 MW inverter units. Each 1.56 MW inverter will be connected to 289 strings and each string contains 20 photovoltaic modules. Each two 1.56 MW inverters will be equipped with a 3.15 MVA three windings unit transformer that allows raising the generated voltage from 0.69 kV to 33 kV depending upon the tap setting, with settings of 5 taps, each with 2.5 % available with 5 % short circuit impedance. The zero sequence impedance values are assumed to be 90% of the positive sequence values. The delivery station will be connected with PCC substation located by approximately 13 km double circuit overhead transmission line (OHTL). The substation consists of two 80 MVA, 33/132 kV grid transformers which step up the voltage to 132 kV. The maximum and minimum tap settings were given in as +/-15% with a total of 30 steps, each step being 1%with about 13 % short circuit impedance. The impedance values have been calculated on 80 MVA system base. A 45 MVAr capacitor bank has been already connected to the PCC in the transmission grid.

Figure 1 shows the 33kV collector array cables. The design cabling arrangement of internal collectors is made up of 400 mm2 cables, Aluminium conductor, single core, and XLPE cable installations. The cross-sectional area of each circuit of the OHTL is 200 mm2. The model of transmission grid for the year of 2016 including all generation plants has been implemented in the Power system analysis software. This grid model is incorporated with all the renewable projects committed in the period of 2014-2016 to the grid. The composite control farm of the static generator (Photovoltaic Generator) is presented in Fig.2. This model is the manufacturer's controller to be used in the planned plant with the aim of evaluating the influence of inverters on the transmission grid. It includes the static behavior with considering the inverter capability curve (before the L-C output filter), shown in Fig.3, which has been provided by manufacturers. In addition, the model includes RMS and EMT behavior and the shown controllers.

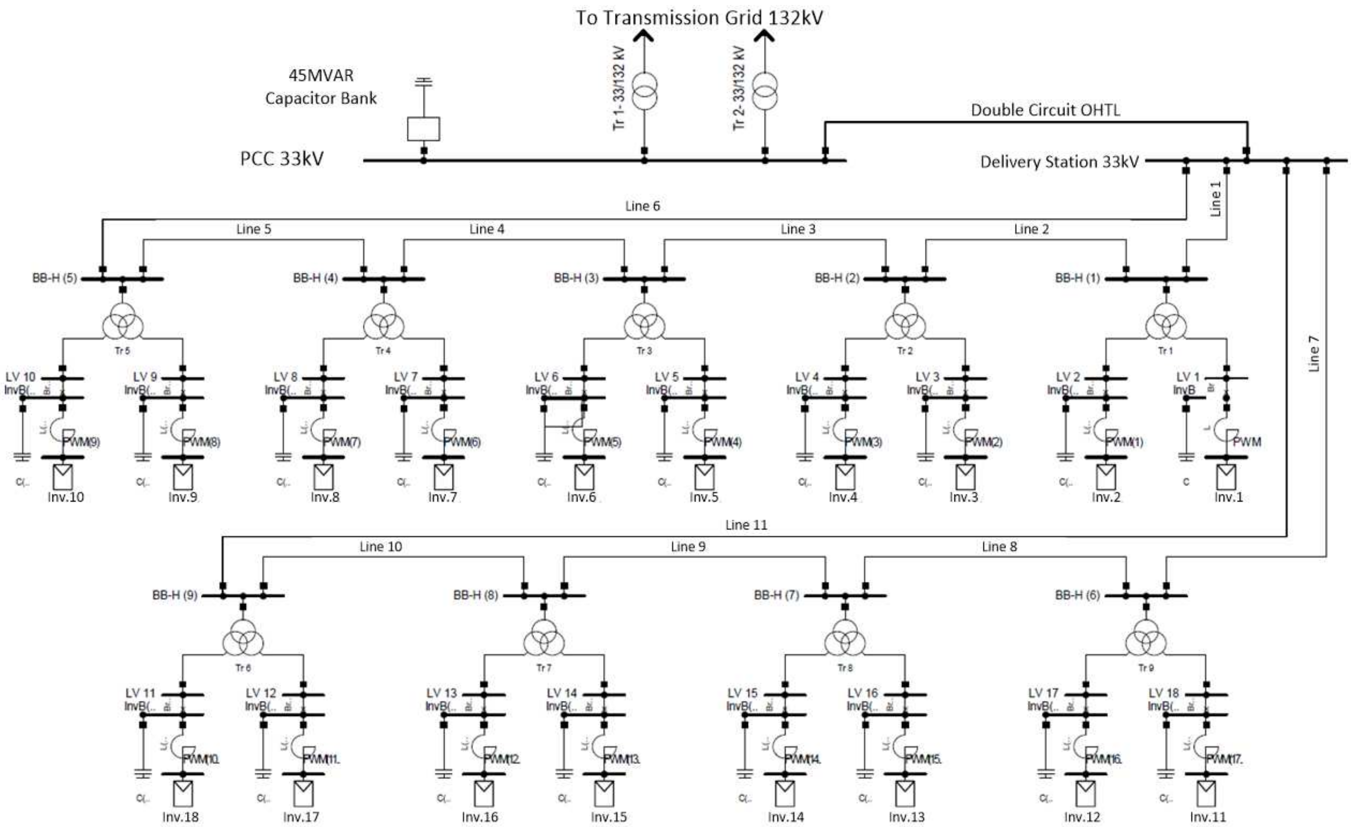



**Fig. 1.** SLD of the photovoltaic plant implemented by DIgSILENT.

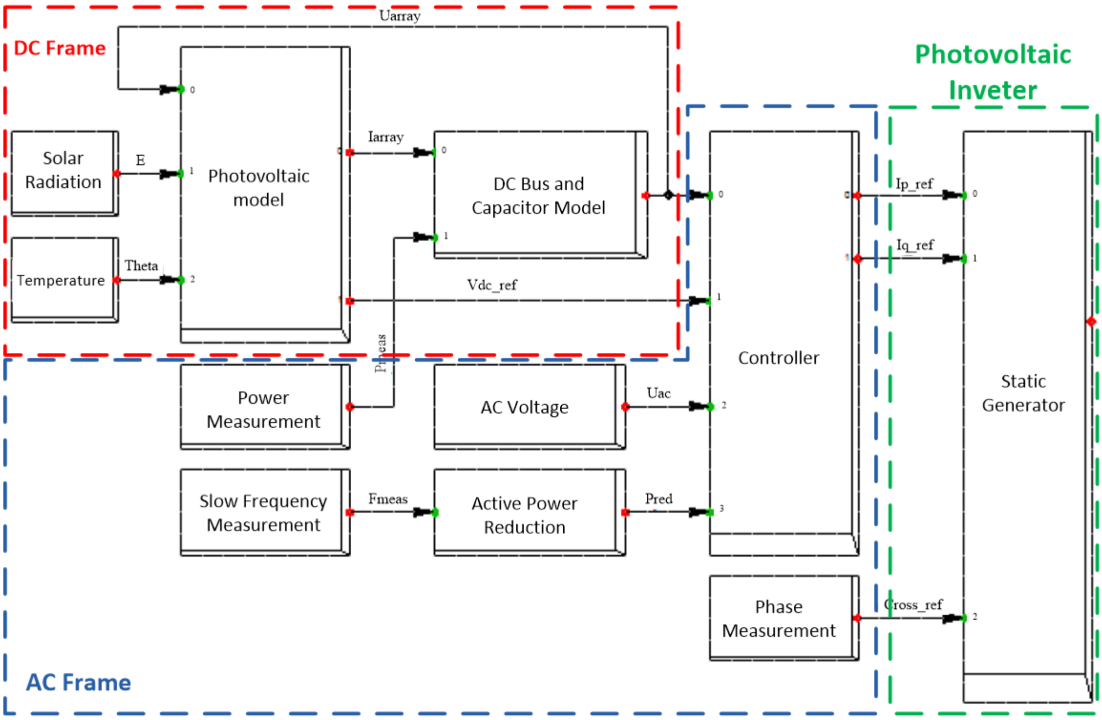



**Fig. 2.** Composite control farm of the photovoltaic generator.

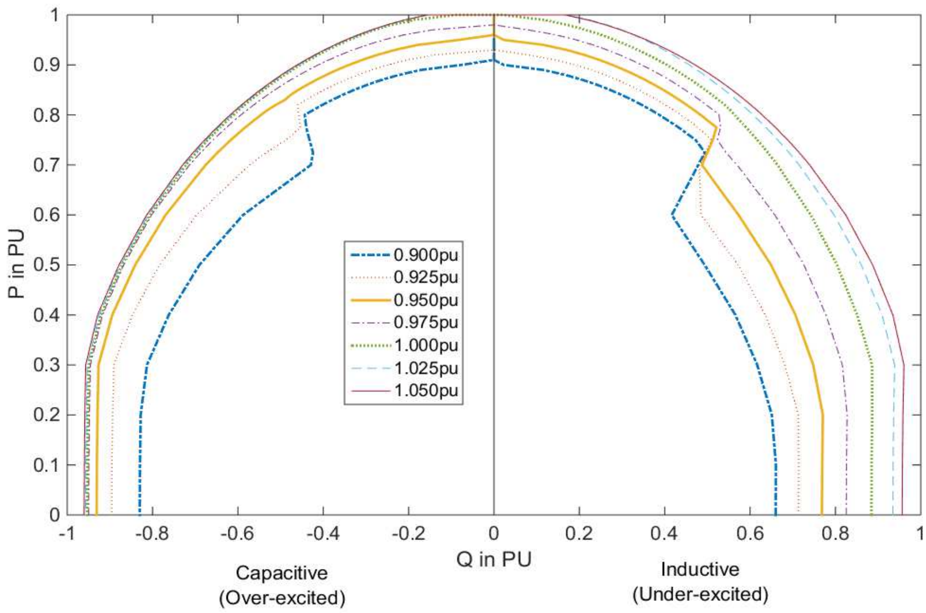



**Fig. 3.** Capability curve of the photovoltaic inverters with different voltage level.

## 3. Transformer Modelling

The inrush current magnitude and duration when a transformer is energized are affected by four factors which are the starting time of energization, the transmission system impedance, and the energized transformer non-linear saturation characteristics, and the residual flux in the core of the energized transformer. First and second factors are determined by the circuit breakers and the grid characteristics to which the transformer is energized, respectively. Other factors are dependent upon the magnetic core characteristics of the energized transformer. The required parameters are the core loss and the magnetizing current at rated voltage, the magnetization curve, and its knee point, and the saturated air reactance of the windings that are the most important factor in determining the peak inrush current. The total resistance of the transmission grid and the energized transformer is the key of determining the decay time of the inrush current [8].

### *3.1. Representation of transformer core saturation*

The real non-linear characteristic of the transformer core is shown in Fig.4.a. This is the relationship between flux and current. The air core or saturated winding inductance $L_A$ is represented by the straight line which intersects the flux axis at $\Phi_K$. The knee point is defined by $\Phi_M$ and $I_M$ which represent the maximum of magnetizing flux and current at rated voltage. An asymptotic function for current in the non-linear saturating region LS can be defined if $L_A$, $\Phi_K$, $\Phi_M$ and $I_M$ are known. The non-linear characteristic of the transformer core is specified in the used program using these variables.

The saturation of the transformer core could be represented by a varying inductance which is connected across the transformer core and calculated at each time step depending on the conditions of the core flux. But this method is computationally expensive. Another method is usually used to represent saturation of the transformer core by a dependant current source as shown in Fig.4.b. The flux is calculated as the integral of the winding voltage. The magnetizing current characterized by the current source $I_S(t)$, is related to the flux through the non-linear $\Phi_S$ – $I_S$ characteristic which can be derived from the voltage and current measurements taken during a no-load by the manufacture, i.e. open circuit, test [8].

(a)

(b)

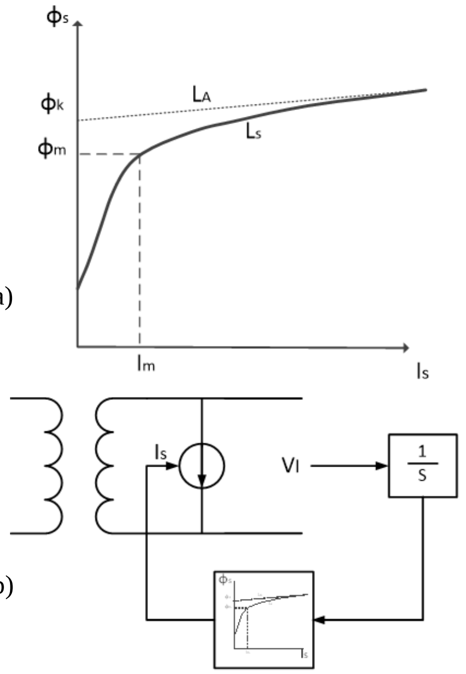



**Fig. 4.** Saturation characteristic of transformers core;

(a) Curve (b) Modeling.

*3.2. Representation of residual flux*

The residual flux effect is modeled by injecting a DC component of current into the winding of the transformer model on which saturation is modeled. This current delivers the ampere turns required in the model to establish the desired level of residual flux linkage within the transformer core. This is generally considered to be the “worst case” that might be expected on any random transformer energization [8]. The residual flux is simulated in the simulation program by defining a parameter event of the energized transformer and set the variable psimd for residual flux with the highest value 0.9.

The knee point voltage and linear reactance have values 1.2 and 500 pu and 1%, respectively, for 2.35MVA step-up three winding unit transformer. For 80 MVA grid transformers, the knee point voltage and linear reactance have typical values of 1.15 and 500 pu and 1%, respectively. Saturated reactance and saturation exponent are assumed 0.25 pu and 15, respectively. This approach would enable the calculation of total inrush current and resultant voltage dip at the PCC during the energization of different numbers of the transformer to be readily made available for further analysis.

## 4. Sudden Voltage Changes

Sudden voltage changes study provides monitoring of voltage changes at the time of unit transformer energization that could be a nuisance to the network and mitigation of the violated changes according to the requirements specified in the grid codes. Voltage flickering provides an assessment of the calculated short-term flicker and long-term flicker and assessing these against the grid code requirements. This paper presents the results of the suite of analysis studies that has been carried out for the photovoltaic plant to assess its performance against the Jordanian grid code requirements. Sudden voltage changes and voltage flickering studies are carried out to ensure that the photovoltaic plant will comply with the relevant requirements specified in the FICHTNER grid code [6] and Engineering Standard P28 [9].

It was assumed in this study that the energization is compliant if the voltage step change (sudden voltage change) is less than 2% after energization of a unit transformer and less than 5% after energization of the photovoltaic plant. It should be noted that the voltage changes would dependent upon the external grid characteristics. The aim of these studies is also to show approximately how many transformers can be energized at the same time whilst still meeting the grid requirements. It is also worth noting that the magnitude of the inrush current strongly depends on the exact time that electrical connection to the network is made. If a transformer happens to have some residual magnetism in its core at the moment of connection to the network, the inrush current could be very different.

*4.1. Scenario 1: single unit transformer energization results*

In this scenario, a single transformer has been energized. Figure 5 shows the voltage change when a single transformer is energized after 0.1 seconds under intact network conditions at fault level. The steady-state voltage on the 33kV bus is 1.0 pu and the maximum voltage after energization is 1.008 pu, giving a voltage rise of 0.8% on the 33kV bus. The voltage rise is due to the capacitance of the internal 33kV cables and 13 km OHTL connecting the plant to 33kV PCC and due to the 45 MVAr Capacitor Bank connected at PCC. The minimum voltage after energization is 0.988 pu, giving a voltage dip of 1.2% on the 33kV bus. The voltage dip is due to inrush current. The voltage rise at the PCC caused by a single unit transformer energization is within the 2% of the grid code. Figure 6 shows the current flow during transformer energization, with a maximum current of 101A.

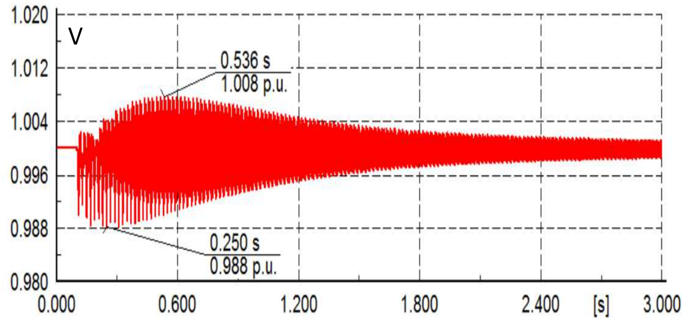



**Fig. 5.** Voltage changes at PCC after single transformer energization.

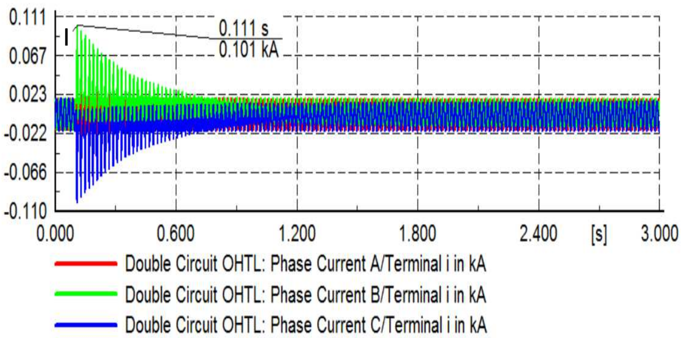



**Fig. 6.** Current flows after single unit transformer energization.

Figure 7 shows the variation of the voltage changes calculated at the PCC against the number of energized unit transformers. Grid code requirements for photovoltaic plants allow for a maximum of 2% transient voltage changes, which is shown in Fig.7 as a dashed red line. The voltage rise and voltage dip on the PCC bus when energizing two transformers simultaneously are 2.3% and 1.5%, respectively. The voltage rise violated the maximum permissible voltage change. From the voltage changes calculated at the PCC during the transformers energization, only one transformer could be energized at the same time. In accordance with the grid code, there must be at least 150 seconds between each single transformer energization.

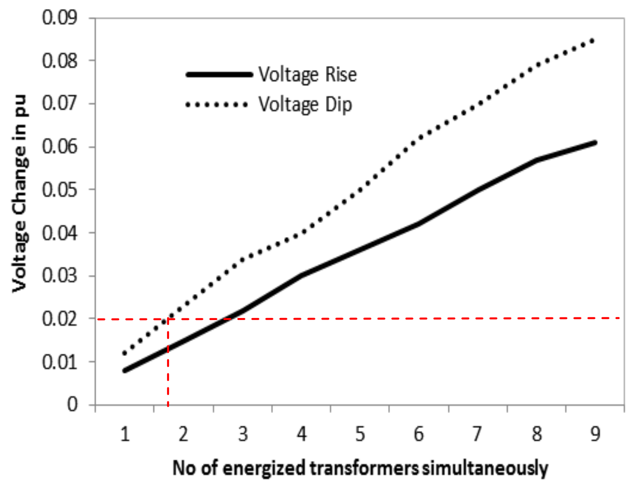



**Fig. 7.** Variation of voltage changes with the number of energized unit transformers.

*4.2. Scenario 2: the plant energization results*

In this scenario, the main circuit breaker that connects OHTL with the PCC has been closed with connecting HV side of all unit transformers or all unit transformers have been energized at the same time. Figure 8 depicts the voltage change when the plant is energized after 0.1 seconds under intact network conditions. The steady-state voltage on the 33kV bus is 1.0 pu and the minimum voltage after energization is 0.913 pu, giving a voltage dip of 8.7 % on the 33kV bus and maximum voltage reach to 1.063, giving a voltage rise of 6.3 %. The voltage changes at the PCC caused by the plant energization are higher than the grid code requirement (5 % due the switching the entire plant). Figure 9 shows the current flow during transformer energization, with a maximum current of 773 A.

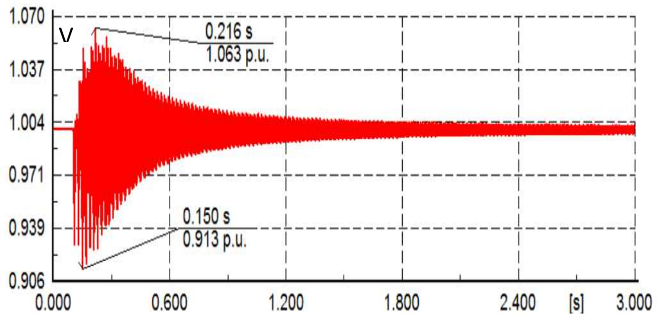



**Fig. 8.** Voltage changes at PCC after plant energization.

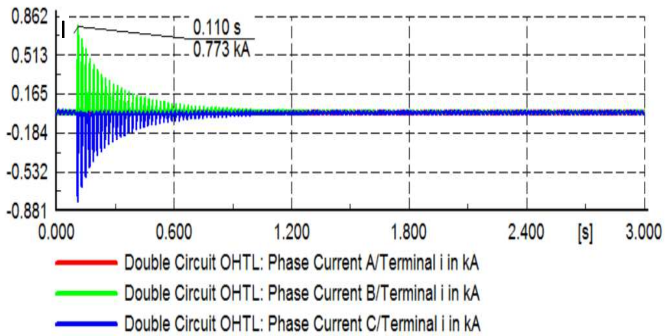
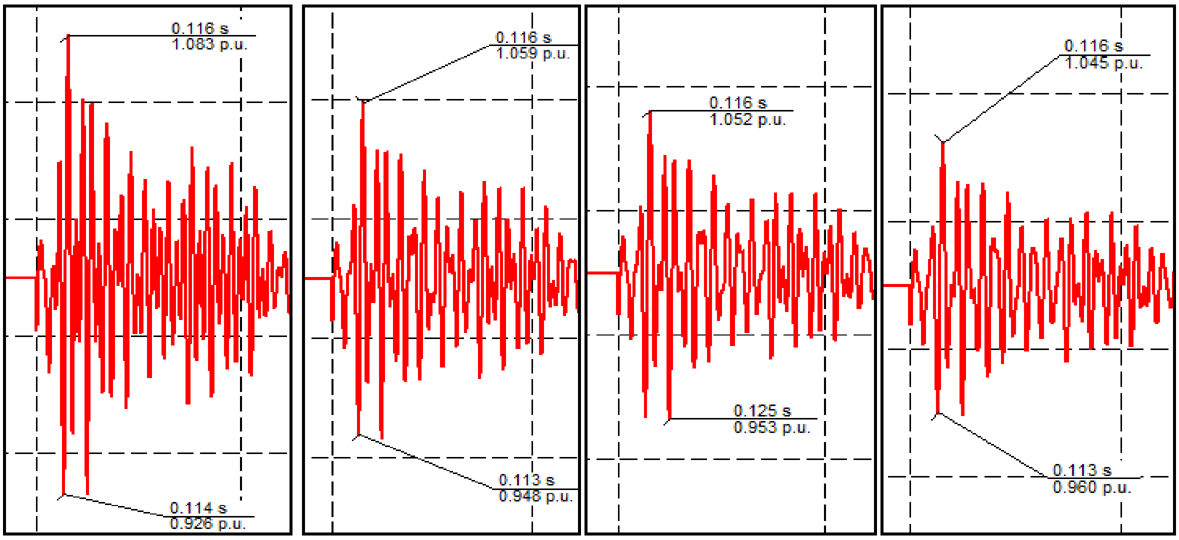



**Fig. 9.** Current flows after the plant energization.

In general, mitigation of transient voltage changes is planned usually by the closing resistors that are inserted in series with the cable connecting the transformer during the energization, normally being short-circuited, thereby damping the switching voltage changes. This resistance is called pre-insertion resistor. Another method could be used to mitigate the transient voltage changes by means of synchronized switching controllers in energizing and de-energizing procedures. Synchronized circuit breakers can control the point-on-wave position to mitigate harmful transients. The suitable instant for controlled switching is the time in which the voltage across the circuit breaker contacts for each phase is zero and the predicted time span between the closing instant of the first and the last pole is as small as possible. The third method is shunt reactor to damp the transient voltage changes and to keep the system voltage within the permissible limits. Finally, the surge arrester provides a path to earth which removes the excessive charge from the system [10], [11], [12], [13]. All previous methods have been compared economically. The pre-insertion resistor is recommended to limit the transient voltage changes in the current study, because it is the most economical solution. The value of pre-insertion resistor effect was examined by changing the value of the resistance from 0 to 500 ohms [12].

Figure 10 is the voltage change at PCC after the plant energization with different values of the Pre-Insertion Resistor with insertion time 20 milliseconds. Based on the study results, as shown in Fig.10, a breaker is to be ordered with specified values of 150 Ohm Pre-Insertion Resistor and a minimum of 20 milliseconds insertion time. The voltage rise at the PCC when the plant is energized with 150 ohm Pre-Insertion Resistor is 4.5 %. The voltage dip at PCC is 4.0 % when the plant is energized with 150 ohm Pre-Insertion Resistor. These values are within the grid code requirement (5 % due the plant switching). Based on these values, the main breaker at PCC is to be ordered with specified values of 150 Ohm Pre-Insertion Resistor and a minimum of 20 milliseconds insertion time.




(a) With 50 ohm (b) With 100 ohm (c) With 120 ohm (d) With 150 ohm

**Fig. 10.** Voltage change at PCC 33kV after the plant energization with different values of Pre-Insertion Resistor; (a) 50 ohm, (b) 100 ohm, (c) 120 ohm, and (d) 150 ohm.

## 5. Flicker Analysis

In order to check the compliance of the relevant sections of the Jordanian grid code, the short-term flicker severity and long-term flicker severity are concerned a flicker assessment which has been carried out on the power system model of the photovoltaic plant. As the magnitude and frequency of supply voltage fluctuations increase it will cause consumers to notice that their lights are flickering. All generators must comply with the FITCHNER Grid code which sets limits on the voltage flicker. There are two important parameters constrained in grid code; PST, the short-term flicker severity (typically measured over a 10 minute period) and PLT, the long-term flicker severity (typically measured over a 2 hour period) [14]. In the case of the photovoltaic plant, both the parameters of short-term and long-term values are assessed.

The PST values are calculated as follows:

$$PST = \sqrt{\Psi_{0.1}P_{0.1} + \Psi_1 P_1 + \Psi_3 P_3 + \Psi_{10} P_{10} + \Psi_{50} P_{50}} \quad (1)$$

Where Ψi is the weighting coefficient of the ith percentile exceedance flicker level (Pi). The percentile points are calculated from the instantaneous flicker, which is a measure of flicker over a very short period (typically 10 milliseconds). PST is dimensionless and measured in per units (pu); a PST value of 1.0 pu being the threshold of human perceptibility. The PLT value can be derived from the PST using the below formula:

$$PLT = \sqrt[3]{\left(PST^3/12\right)} \quad (2)$$

Based on the FITCHNER standard the PST value must not exceed 1.0 pu at the PCC of the photovoltaic plant while PLT should be less than 0.46 based on Engineering Standard P28.

The assessment is based on a statistical approach. In order to proceed with the studies, a set of active power measurement would be required for photovoltaic modules; these active power measurements should be provided for a continuous 10 minutes period as a minimum with at least 10 Hz resolution giving the total number of measurements points of 6000. The procedure itself requires a series of power flow studies based on the active power measurements. Ideally, 6000 measurements need to be provided hence 6000 power flow studies need to be assessed.

For the assessment of the flicker (calculation of PST values) at the PCC of the photovoltaic plant a Flickermeter tool in Microsoft Excel format has been developed. The input data for the Flickermeter are the active power flow at the PCC and the voltage deviation (from 1.0 pu nominal value) at the PCC caused by the associated active power flow. The active power flow (P) needs to be entered in MW while the voltage deviation (dV) as % (from the nominal value). In order to calculate the PST values for 10 minute periods, the data needed are entered in 10 Hz resolution, giving a total number of 6000 data points for each PST value. The results (P at the PCC and deltaV % at the PCC) have been taken and entered into the Flicker meter tool and the PST value has been determined. Based on the PST value, the PLT have been calculated according to the formula provided above.

According to the above-described methodology, the PST value was calculated as 0.20 pu and the PLT as 0.09 pu. The values of PST and PLT are well below the FITCHNER code's values of 1.0 pu and 0.46 pu respectively.

## 6. Conclusions

The voltage rise when the single transformer is energized is 0.08% at PCC and voltage dip is 1.2%. This value is within the the grid code requirement (2 % due to single transformer switching). The voltage rise when the photovoltaic plant is energized is 6.3% at PCC and voltage dip is 8.7%. This value is higher than the grid code requirement (5 % due to switching the entire plant). The voltage dip is due to inrush current. Also, it should be noted that the capacitance of the internal 33kV cables, the capacitance of 13 km OHTL connecting the plant to PCC and the 45 MVAr Capacitor Bank connected at PCC have a significant effect on the voltage rise during energization. In accordance with the grid code, there must be at least 150 seconds between each single transformer energization.

All methods of mitigating the sudden voltage changes have been compared economically. The pre-insertion resistor is recommended to limit the transient voltage changes in the current study, because it is the most economical solution. The closing resistors are inserted in series with the OHTL, normally being short-circuited after 20 milliseconds, thereby damping the switching overvoltage. The Pre-Insertion Resistor is initially in the range from 0 Ω to 500 Ω. Based on the study results, the main breaker that connects the OHTL with PCC is to be ordered with specified values of 150 Ohm Pre-Insertion Resistor. The voltage rise when the plant is energized with 150 ohm Pre-Insertion Resistor is 4.5 % at the PCC. The voltage dip when the plant is energized with150 ohm Pre-Insertion Resistor is 4.0 % at the PCC. These values are within the grid code requirement (5 % due the plant switching).

The short-term flicker PST (over 10 minutes period) has been determined as 0.20 which is below the P28 Engineering recommendation limit 1.0. Also, the long-term flicker PLT has been calculated as 0.09, which is below the value of 0.46 provided by the FICHTNER code. Therefore, we can state that the photovoltaic plant is compliant with the FICHTNER standard for PLT. Furthermore, it is also compliant with the PST requirements of Engineering Standard P28.

To conclude, a more accurate decision-making of the photovoltaic plant complying with regulator grid codes and its grid connection design could be taken by the transmission system operators from these accurate results guaranteeing that there are no violations during different operating conditions and in the switching cases.

## Acknowledgements

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## References

[1] M. Elshahed, H. Zeineldin and M. Elmarsfawy, "A Bivariate Chance Constraint of Wind Sources for Multi-Objective Dispatching," Smart Grid and Renewable Energy, Vol. 4, No. 4, 2013, pp. 325-332.

[2] M Farhoodnea, A. Mohamed, H. Shareef1, H. Zayandehroodi, "Power Quality Analysis of Grid-Connected Photovoltaic Systems in Distribution Networks," Przegląd Elektrotechniczny Journal, 2013, pp. 208-213.

[3] M. Eltawil, Z. Zhao, "Grid-connected photovoltaic power systems: Technical and potential problems—A review," Renewable and Sustainable Energy Reviews, Vol. 14, 2010, pp. 112–129.

[4] P. González, E. Romero, V. M. Miñambres, M. A. Guerrero and E. González, "Grid-connected PV plants. Power quality and technical requirements," Electric Power Quality and Supply Reliability Conference, Rakvere, 2014.

[5] R. Dash, S. C. Sahoo, S. M. Ali and A. K. Mohanta, "Problems associated with grid integrated solar photovoltaic system," Electrical, Electronics, Signals, Communication and Optimization Conference, Visakhapatnam, 2015.

[6] FICHTNER, Assessment for Grid Code Compliance for photovoltaic Plants in Jordan 11587582-v1, Jul. 2014.

[7] National Electric Power Co., NEPCO Transmission Grid Code, 2010.

[8] R.A. Turner, K.S. Smith, "Assessing P28 Guidelines for Renewable Generation Connections," International Conference on Power Systems Transients, Netherlands, Jun. 2011.

[9] Engineering Recommendation P28, Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the UK, Sep. 1989.

[10] T. Kuczek, M. Florkowski and W. Piasecki, "Transformer Switching With Vacuum Circuit Breaker: Case Study of PV Inverter LC Filters Impact on

Transient Overvoltages," in IEEE Transactions on Power Delivery, vol. 31, no. 1, Feb. 2016, pp. 44-49.

[11] E. Awad, E. Badran, F. Youssef "Mitigation of Temporary Overvoltages in Weak Grids Connected to DFIG-based Wind Farms," Electrical Systems Journal, Vol. 10, 2014, pp. 431-444.

[12] J. Hu, B. Bisewski, D. Maki, M. Marz, "Mitigation of Voltage Drop Using Pre-Insertion Resistor during Large Transformer Energization in a Weak System: Simulation and Field Verification," International Conference on Power Systems Transients, Netherlands, Jun. 2011.

[13] P. Mestas, M.C. Tavares, "Comparative Analysis of Control Switching Transient Techniques in Transmission Lines Energization Maneuver," International Conference on Power Systems Transients, France, Jun. 2007.

[14] M. Kopicka, M. Ptacek and P. Toman, "Analysis of the power quality and the impact of photovoltaic power plant operation on low-voltage distribution network," Electric Power Quality and Supply Reliability Conference, Rakvere, 2014.