Voltage Profile Optimization with Coordinated Control of PV Inverters

Naser Hashemipour, Jamshid Aghaei, Taher Niknam, Mohammad Askarpour
Shiraz Univ. of Technology
Shiraz, Iran
aghaei@sutech.ac.ir

Miadreza Shafie-khah
Univ of Vaasa
Vaasa, Finland
miadreza@gmail.com

Fei Wang
North China Electric Power University
Baoding, China
feiwang@ncepu.edu.cn

João P. S. Catalão
INESC TEC and FEUP
Porto, Portugal
catalao@fe.up.pt

2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe) | 978-1-6654-3613-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/EEEIC/ICPSEurope51590.2021.9584552

***Abstract*—Due to the fact that distributed generation (DG) has many advantages in the power systems, DG implementation is indispensable. However, it could introduce some problems in the system such as changing the voltage profile. In this paper, an optimum voltage control model based on photovoltaic (PV) inverters is proposed. In the daytime, the PVs inject current to the distribution network, and therefore, in that time there will be a potentially high voltage profile. In contrast, in the evening, the customers consume more power and PV has nothing to compensate, and a low voltage profile is seen. This work seeks to provide a power control scheme for the active and reactive power of the inverter and integrates it with a night mode control of PVs, by a modified hysteresis controller. To gain a suitable voltage profile, all voltages of the buses should get close to the reference voltage. For preventing the interference between different inverters in the network, this control scheme is applied to the whole network coordinately. The 33-bus IEEE system is used to test the performance of the control model, and the results show the effectiveness of the proposed model.**

Keywords—Distribution network, Hysteresis controller, Inverter, Photovoltaic system, Voltage control.

I. INTRODUCTION

A. Literature Overview

Electrical power consumption is increasing each year and the power production should increase coordinately. The central power plants have some problems such as low reliability, air pollution, power losses, low security, among others [1]. These problems lead power systems to use more distributed generations (DGs), which have lower power production. These power productions have their own problems [2], such as if they inject power to the system with no control scheme, the voltage could go out of the limits. So having a control solution to alleviate this problem is necessary. Many studies have been taken place in recent years.

Reference [3] has coordinated DGs and tap-changers to correct the voltage profile and with minimizing the number of taps objective. Fewer taps mean more useful life of the transformer. Reference [4] has used the voltage sensitivity matrix to control the active and reactive power of each inverter to control the bus voltages locally.

In reference [5] a control algorithm for coordinated On-load tap changer (OLTC) voltage control and reactive power compensation was proposed. The voltage control of OLTC was based on the state estimation for determining the network voltage. Reference [6] has developed a strategy to control the over-voltage problem in the distribution network with PVs based on energy storage. The energy storage saved the power difference between the PVs production and local load on that bus. The local load (load and battery charging) matched the PVs power production, therefore the reverse power problem and over-voltage problem were solved as much as possible. Furthermore, in the peak load, the reserved energy was successfully used. Reference [7] has proposed a coordinated control method with global and local controls. The global control role was to regulate the feeder voltages within the required limits, and the local control regulated the state-of-charge of each energy storage system within a desired range. To correct the voltage profile, in [8] was proposed a method base on the local (zone) control concept; which was able to utilize the ability of DG as a voltage regulator, minimizing the interaction with other active devices, such as an OLTC and a voltage regulator.

Reference [9] has proposed a coordinated control of PV and battery energy storage to cope with the voltage profile problems. The proposed model was tested on rural and urban distribution networks. The result has shown the reactive capability of PV inverter, combined with droop-based battery energy storage system, it was enough to keep the acceptable voltage limits. Reference [10] has proposed a night mode control scheme for inverter VAR compensation which allows the inverter to draw a little portion of active power from the network to regulate its direct current (DC) link and injects the desired reactive power to the network.

In [11], a voltage control method has been presented in the distribution networks with the participation of PVs and tools of voltage control such as the static-voltage-regulator (SVR). The main objective of this work was to minimize the losses in power systems. To this end, using the load prediction and DGs generation, by taking a genetic algorithm, the appropriate reference values were calculated for the main controllers of the system for a period of time, considering as well the possibility of errors in predictions. However, the reference values may not produce an optimal response on the network. To solve the problem, fuzzy controllers have been designed for the reactive power inverters controlling. In [12], a compatible approach has been provided for adjusting the system voltage for loss reduction. The proposed method has chosen the objective function between loss reduction and voltage profile improvement, based on the closeness of buses voltage with the bus voltage of the main station.

B. Contributions

The current work is concentrated on the PV's inverters coordination with other devices to attain the best voltage profile. The proposed inverter's controller works in both daytime and night-time modes. Moreover, the controller in addition to controlling the active power can control the reactive power and the DC-link capacitor voltage.

In the daytime when PVs are producing power to the distribution network and affecting the voltage profile, the PVs controller sets the active and reactive power on the optimum values to neutralize the PVs effects on the voltage profile. In the night-time when PVs are off, the proposed controller is adjusting the DC-link capacitor voltage on a suitable value to enable the inverter for producing reactive power, therefore the need for shunt reactors to overcome the over-voltage of low load in this period decreases.

J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under POCI-01-0145-FEDER-029803 (02/SAICT/2017).

Another feature of this paper is the high-speed convergence of the solving problem in the General Algebraic Modeling Language (GAMS) software by linearizing the objective function.

In Section II, the active and reactive power control methods of inverters are concisely explained. Next, the procedure of the reactive power control method in the night mode condition is described. The proposed method is introduced in Section III, and in the Section IV the results are shown. Finally, Section V provides the main findings obtained in this proposed work.

II. The Inverter's Active and Reactive Power Control Methods

The control ability of active and reactive power in the inverters is the control of instantaneous active and reactive power which has a lot of advantages like voltage control. This ability gives to the inverter by a good control scheme with a suitable controller. There are two control modes for inverters [13] that are compared as follows.

A. Voltage Control Mode

In this mode, control is based on the angle and amplitude of alternate current (AC) voltage at the inverter's terminal. The advantage of this mode is that, if the AC voltage amplitude of the inverter and its angle is near the network voltage amplitude and angle, the controls of amplitude and angle are independent therefore there need to be two controllers and this makes the control scheme easy.

The disadvantage of this model is the absence of any feedback from the output inverter current, consequently, in sudden reference changing or any fault in the network, the inverter is not protected in an over-current situation. The block diagram of the voltage control mode is shown in Fig. 1.

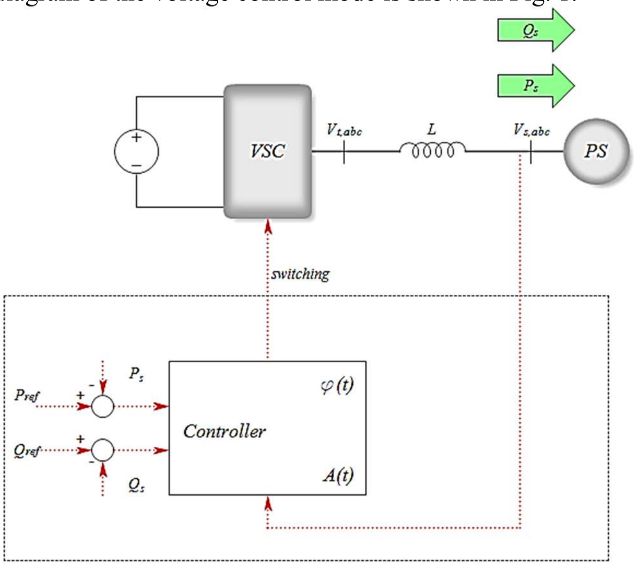

Fig. 1. The voltage control mode.

B. Current Control Mode

The controller in this mode measures the network voltage and sets the current amplitude and its angle to suitable values. Therefore, this inverter is protected in over-current conditions. Because the reference current is sinusoidal and in order to use linear control methods and lowering the number of controllers, the control scheme is designed in ∝b reference. The block diagram of the current source mode is shown in Fig. 2.

C. The Proposed Model

One of the grid problems is the over-voltage in low-load hours. Compensating equipment like shunt-reactors is used to mitigate this over-voltage. Since the low load condition occurs in midnight hours and the solar inverter capacity that is shown in Fig. 3 is available, it can operate as a shunt-reactor. For this purpose, the DC-side voltage of the inverter must be kept in the allowed range. So a hysteresis controller is proposed to control the DC-link capacitor's voltage.

The proposed model is a voltage control scheme for coordinating DGs and determining their optimum set points, and furthermore, designing a controller for implementation of this control model. The purpose of designing a controller is to control the active and reactive power in both daytime and night-time modes. To this end, the proposed controller is a combination of current control mode and modified hysteresis control. The block diagram of the proposed controller is shown in Fig. 4. To activate the inverter in the night-time, the voltage of the DC side of the inverter must be kept in the allowed range. So, to charge the DC side capacitor, the active power reference should be set on a negative value, meaning that it has to draw some active power from the network. This value is depended on the inverter's efficiency.

In fact, the drawn power is the number of power losses of the inverter which in the most efficient inverters is about 5%. For fast charging, this value is multiplied in a suitable gain (2 is good). S_1 and S_2 switches prevent the interference of the daytime and night-time modes. In the daytime mode, the switch S_1 is closed and the switch S_2 is opened.

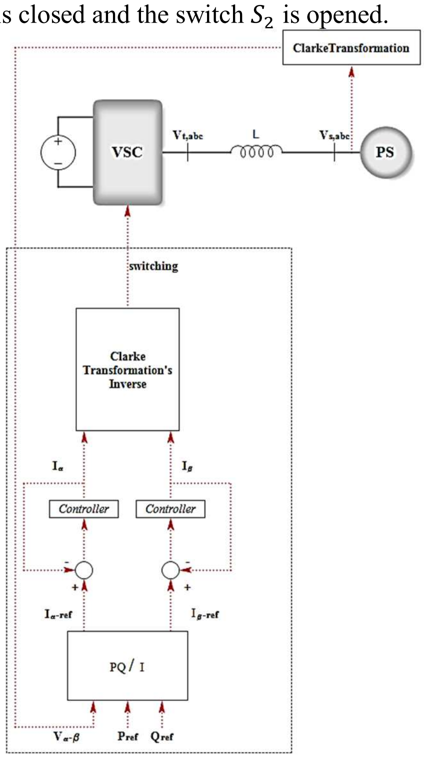

Fig. 2. The current control mode.

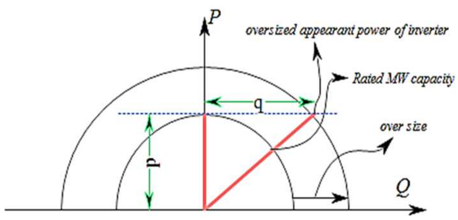

Fig. 3. The capability curve of the inverter.

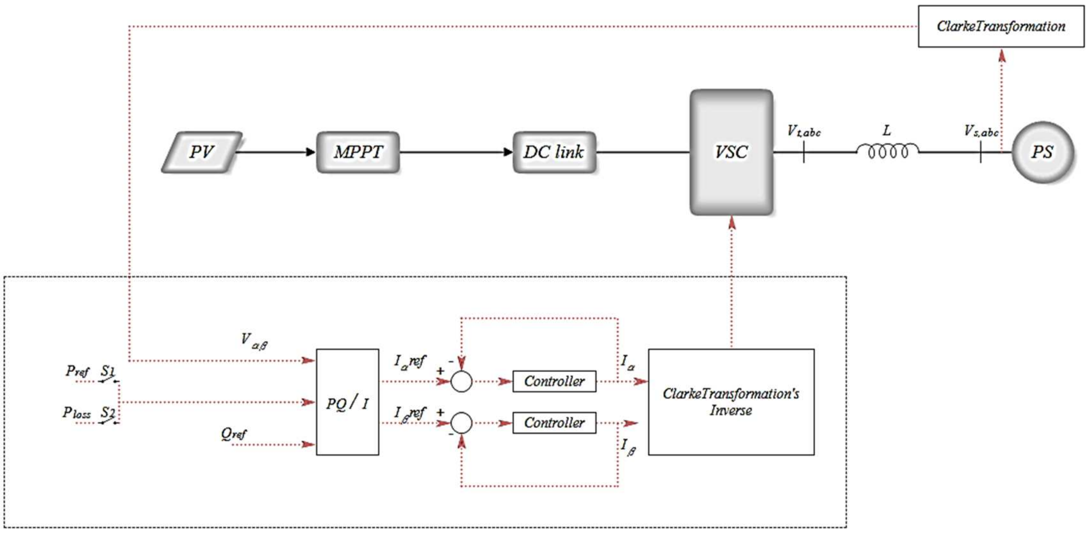

Fig. 4. The proposed controller.

Also, switch S_1 is opened and S_2 is switched properly in night-mode to keep the voltage of the DC-link capacitor in a suitable range. In fact, the modified hysteresis control implemented by S_2 is responsible for keeping the voltage of the DC-link capacitor in an acceptable range. The proposed hysteresis control has a set-point which is the optimum voltage for the DC-link capacitor.

If the capacitor voltage goes below to the set-point, the switch S_2 gets closed, and when it reaches the set-point the switch S_2 gets opened. If there was not any limitation on the switching frequency the voltage would set exactly on the set point. But in reality, it depends on the frequency of the switch, i.e., higher frequency means lower voltage tolerance.

If each DG controls its voltage independently and without coordination with other devices, there is a probability of DGs interference.

Therefore, in the following, distributed coordination is presented. This coordination is done by an algorithm with the aim of optimizing the voltage profile. The objective function is defined in Equation (1). This objective function is linearized by linearizing techniques.

$$f = \sum_{t=1}^{N_T} \sum_{i=1}^{N_{bus}} (V_{i,t} - 1)^2 \tag{1}$$

where the $V_{i,t}$ is the voltage amplitude of i^{th} bus of network in the time t. In fact, by optimization with the aim of bringing all buses to 1 pu voltage, reference values of inverter reactive powers are determined. Equations (2) and (3) are very important constraints.

Equation (2) limits the voltage in permitted range and Equation (3) is a linearized load flow that models grid topology [14].

$$V_{\min} \le V_i(t) \le V_{\max} \tag{2}$$

$$I = Y_{bus} V \tag{3}$$

The active power reference of daytime mode and night-time mode are related to the switches S_1 and S_2. The active power reference of S_2 is determined constantly by calculating the approximated value of inverter power losses $(\cdot)$ by (4). The Equation (4) is related to the efficiency and input rated power of the inverter.

$$\mathrm{P}_{s_2}^{ref} = 2 \times (1 - \eta_{Inverter}) \times \mathrm{P}_{Inverter}^{Rated} \tag{4}$$

In order to consider an economical usage of initial investment, and prevent wasting the generated power of PVs, the maximum power point of PV is set for S_1 switch. But to do this there are limitations. A very important limitation is the inverter capacity which is mentioned before. Another important limitation is the power flow limitation.

The power flow equations have modeled the network also they have shown the impacts of different elements (like PVs) on the voltage profile, among others. But these equations are nonlinear and cause to slow solving the algorithm and even could not converge to an optimum solution. So it is better to add a linear power flow constraint to the optimizing problem.

III. Controller Design

The proposed controller design is done by the SISO tool in MATLAB software. An appropriate controller must have a low transient and steady-state error.

Fig. 5 shows a block diagram of the closed-loop controller. If Equation (5) equals to one, systems output equals its input. In other words, the error of the system is zero.

$$\frac{I}{I_{ref}} = G_i(S) = \frac{L(S)}{1 + L(S)} = |G_i(S)| e^{j\delta} \tag{5}$$

$$L(S) = K(S)G(S) \tag{6}$$

$K(S)$ is the required controller and $G(S)$ is the inverters transformation function. In order to error zeroing, $L(S)$ must go to the infinity. This condition must be met in grids frequency, So the controller must contain two poles in the form of Equation (7).

$$K(S) = \frac{1}{S^2 + \omega_0^2} H(S) \tag{7}$$

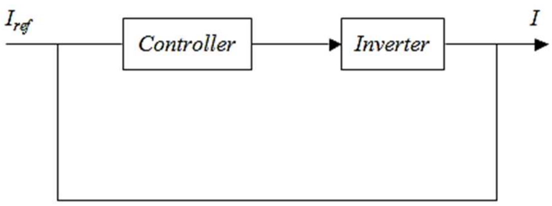

Fig. 5. Block diagram of closed loop controller.

To have a proper bandwidth, ω_0 has been selected equal to 377 rad/s. Now, $H(S)$ should be designed as a stable system. $H(S)$ is designed due to the proposed inverter transfer function in [13]. The simplest choice of $H(S)$ is 1.

Bode's diagram is shown in Fig. 6(a). In this situation, the gain crossing frequency equals 2333 rad/s and in this frequency, the phase margin is negative and the system is unstable. Phase margin can be increased by adding a zero to $H(S)$ for offset inverters pole.

Fig. 6(b) shows that the loop is stable but the intended gain crossing frequency is not reached. So, the gain of 42.272, which was calculated by the SISO tool, is added to the controller. Finally, to having a sufficient phase margin, 45 degrees is added to phase in 2333 rad/s. The final controller can be seen in Equation (8). Hence, Fig. 6(c) shows from the system's Bode diagram that the controller is suitable.

$$K(S) = 42.272 \frac{0.12S + 1}{(0.0027S)^2 + 1} \times \frac{0.001S + 1}{0.00018S + 1} \qquad (8)$$

IV. Simulation Results

To evaluating the proposed model, the IEEE 33 buses network is used. All the busses of this system have 12.66 kV. Three solar power plants are in buses 16, 24 and 30. The peak time load profile is shown in Fig. 7(a). For assuring of the proposed method, the network is tested in 24 hours' period. The Fig. 7(b) shows a 24-hour load profile. The solar output power in per-unit during the 24 hours is shown in Fig. 8.

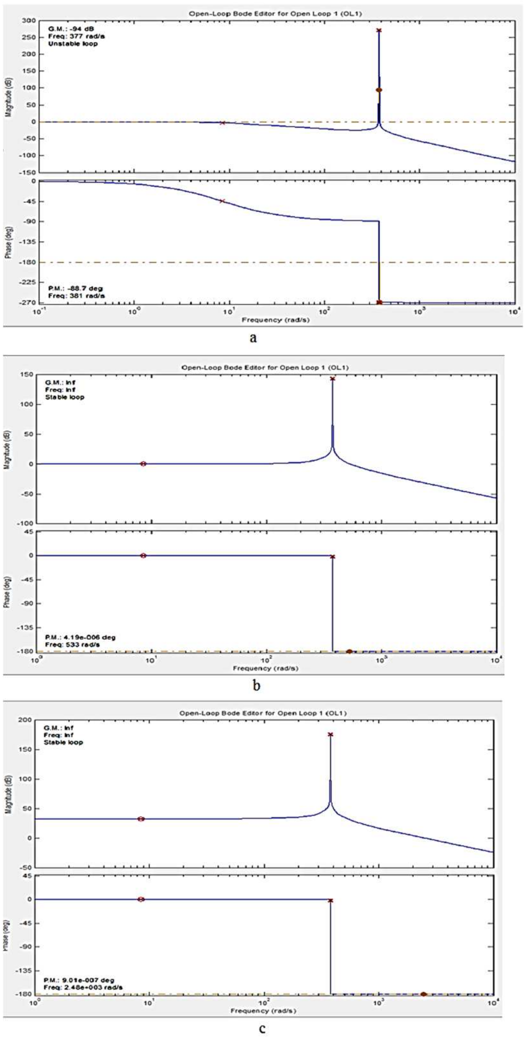

Fig. 6. Bode diagram.

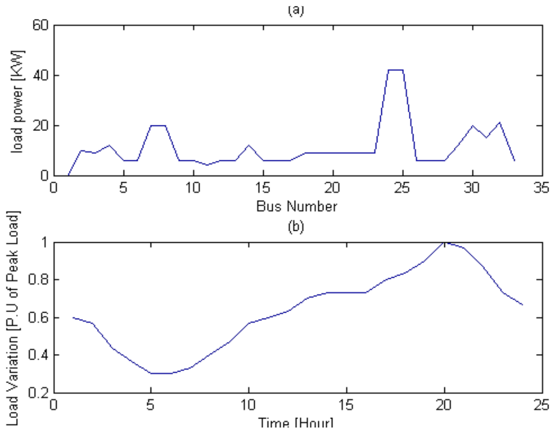

Fig. 7. The peak time load profile (a), 24 hour load profile (b).

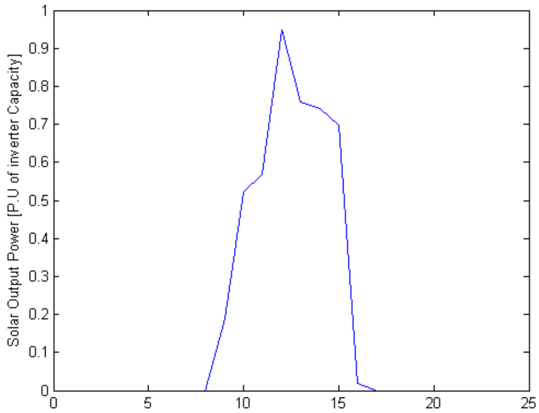

Fig. 8. The solar radiation in 24 hours of a day.

Based on the load profile as well as the amount of radiation during the day, the algorithm has calculated the optimum values of inverters reactive powers and optimum position of tap-changer. Therefore, the optimum load profile is obtained without any inverters and tap-changer interference. According to Fig. 8 most of the time PV does not produce power which is in the night-time mode. As mentioned in Section II B, when PVs do not produce active power the inverter can produce more reactive power.

Moreover, in night-time mode, there is wider flexibility in reactive power generation and voltage profile correction, instead of inverters being off. For instance, the voltage profile of bus 1 (the slack bus), which is mostly related to the tap-charger operation, and bus 16 which is mostly related to the inverter's operation, are studied.

The voltage profile of bus 1and 16 with and without DG are shown in Fig. 9. As it is shown, the tap-changer, which is connected to the first bus, it is increased the voltage to overcome to the voltage drop of the last buses.

Also, on bus 16, the voltage drop is obvious, but it doesn't go outside the limit because of the operation of tap-changer. The presence of PVs with reactive power control leads to a better voltage profile. In times which PVs do not work, the voltage profile is got smoother as the result of the inverter's night-mode effect. The optimum inverters' reactive power values are determined by coordinated control considerations.

The coordinated control algorithm will optimize the voltage profile if the inverters have enough active and reactive power to inject. Fig. 10 demonstrates the ability of the controller to tracing the reference power. As can be seen, the output power of the inverter reaches steady-state 100 kW in just 2 milliseconds.

As mentioned before, the voltage of the DC-link capacitor should be in a specific range so the hysteresis control is proposed. In this work, the voltage range is 450 to 700 Volt and the optimum value is 500 Volt. The proposed modified hysteresis control sets the capacitor voltage on 500 Volt with low deviations which is depending on the switching speed.

Fig. 11 shows that the capacitor voltage is reached the 500 Volt in just 235 milliseconds. This is another advantage of the proposed modified hysteresis control which could reach from zero to optimum voltage in a very-short-time. The conventional hysteresis control takes more time to reach it.

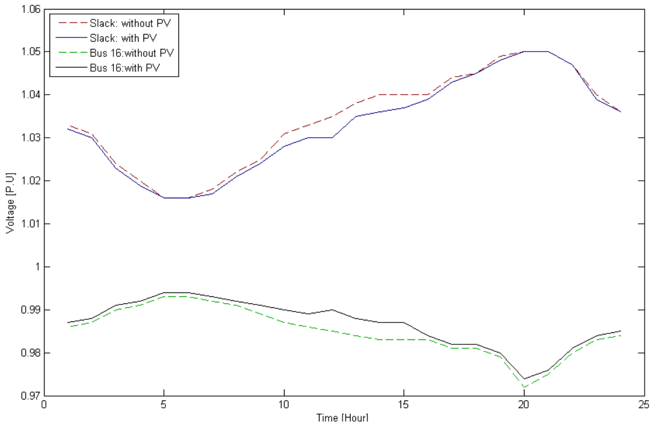

Fig. 9. The voltage profile of bus 1 and 16.

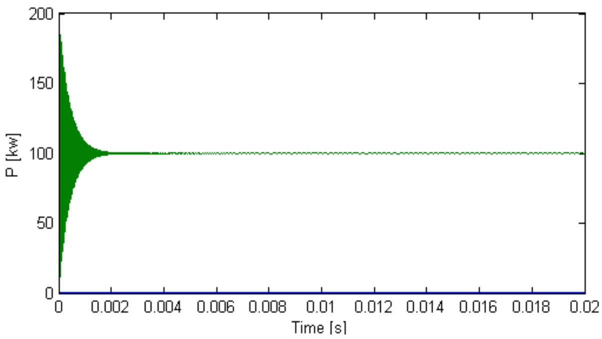

Fig. 10. The active power of three phases inverter during the time.

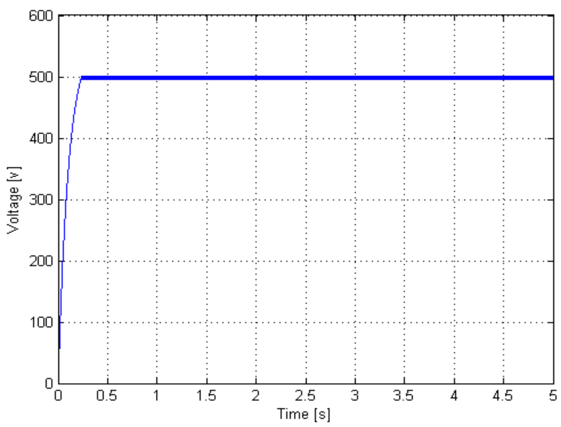

Fig. 11. Modified hysteresis control capacitor voltage.

V. Conclusion

As the use of DGs is growing, the network faces new challenges. One of the challenges of network and consumers is the voltage profile that affects consumers' energy and network security. In this work, the effect of PVs on the voltage profile was evaluated. It was proved that the night-time mode of inverters can help to smooth the voltage profile. The proposed optimization algorithm finds the best values for the reactive power of the inverters and the tap-changer value to reach the best voltage profile. The coordinated control considers all the DGs and tap-changers together as one objective function, instead of letting them work locally. As shown in this work, the coordinated control prevented DGs from interfering with each other. Another contribution of this work is the proposed modified hysteresis control. Setting the capacitor voltage around the optimum value is the first advantage of this proposed control. The high speed of the tracing reference voltage is another advantage of the proposed control. The nominal switching frequency of the switches is the most determinative of these advantages.

References

[1] G. Masters, "Renewable and efficient electric power systems," *John Wiley & Sons*, 2004.

[2] R. Walling and R. Saint, "Summary of distributed resources impact on power delivery systems" *IEEE Trans. Power Delivery*, Vol. 23, No. 3, pp. 1636-1644, 2008.

[3] P. Y. Agalgaonkar, B. C. Pal, R. A. Jabr, "Distribution voltage control considering the impact of PV generation of tap changers and autonomous regulators", *IEEE Trans. Power Systems*, Vol. 29, Issue. 1, pp. 182-192, 2014.

[4] R Samadi, L. Eriksson, B. G. Söder, J. C. Rawn Boemer, "Coordinated active power-dependent voltage regulation in distribution grids with pv systems" *IEEE Trans. Power Delivery*, Vol. 29, No. 3, pp. 1454-1464, 2014.

[5] S. N. Salih and P. Chen, "On coordinated control of OLTC and reactive power compensation for voltage regulation in distribution systems with wind power" *IEEE Trans. Power Systems*, Vol. 31, No. 5, pp. 4026-4035, 2016.

[6] M. J. E. Alam, K. M. Muttaqi, D. Sutanto, "Mitigation of rooftop solar PV impacts and evening peak support by managing available capacity of distributed energy storage systems," *IEEE Trans. Power Systems*, Vol 28, No. 4, pp. 3874-3884, 2013.

[7] Y. Wang, K. T. Tan, X. Y. Peng, P. L. So, "Coordinated control of distributed energy storage systems for voltage regulation in distribution network," *IEEE Trans. Power Delivery*, Vol 31, No. 3, pp. 1132-1141, 2016.

[8] K. M. Muttaqi, D. T. Le, M. Negnevitsky, G. Ledwich, "A coordinated voltage control approach for coordination of OLTC, voltage regulator, and DG to regulator voltage in a distribution feeder", *IEEE Trans. Industry Applications*, Vol. 51, No. 2, pp. 1239 – 1248, 2015.

[9] M. N. Kabir, Y. Mishra, Z. Y. Dong, G. Ledwich, K. P. Wong, "Coordinated control of grid connected photovoltaic reactive power and battery energy storage systems to improve to the voltage profile of a residential distribution feeder", *IEEE Trans. Industrial Informatics*, Vol. 10, No. 2, pp. 967 – 977, 2014.

[10] N. Maknouninejad, I. Kutkut, F. Bartash, "Analysis and control of PV inverters operating in VAR mode at night", *In Proc. IEEE International Conference Publications*, 2011.

[11] A. Vaccaro, G. Velotto, A. F. Zobaa; "A decentralized and cooperative architecture for optimal voltage regulation in smart grids", *IEEE. Trans. Industrial Electronics*, Vol. 58, No. 10, pp. 4593-4602, 2011.

[12] D. H. Spatti, I. N. da Silva, W. F. Usida, R. A. Flauzino; "Real-time voltage regulation in power distribution system using Fuzzy control", *IEEE. Trans. Power Delivery*, vol. 25, no. 2, pp. 1112-1123, 2010.

[13] A. Yazdani and B. R. Iravani, "Voltage sourced converters in power systems," *John Wiley & Sons*, 2010.

[14] S. Bolognani, D. Zampieri, "On the existence and linear approximation of the power flow solution in power distribution networks", *IEEE Trans. Power Systems*, Vol. 31, No. 1, pp. 163-172, 2016.