Voltage Sag Mitigation with DVR optimized in DFIG based Wind Energy System

Hale Bakır[1*]

[1*] Department of Electronics and Automation, Sivas Technical Sciences Vocational School, Sivas Cumhuriyet University, Sivas, Turkey
(ORCID: 0000-0001-5580-0505)

Abstract

One of the most serious power quality problems in electrical networks is voltage drops. The DVR is known as the most common special power devices used in solving these power quality problems. In this study, optimization is made with WCA algorithm in DVR'S control circuit under wind energy system for fast and reliable detection of mains voltage disruptions, voltage drops and voltage spikes, Its performances were evaluated according to conventional PI controller. These control methods can instantly extract the amplitude and phase information of the mains voltage to detect voltage changes quickly and accurately and with the help of this information, The voltage that needs to be injected into the connection point can be obtained. In the simulation study, the tensions produced by DVR in DFIG based wind energy system and injected into the system were also presented using these two different control methods. The superiority of WCA-based PI controller is clearly seen in the results.

Keywords: Voltage sag mitigation, Water cycle algorithm, DFIG based wind system, Optimization

DFIG Tabanlı Rüzgar Enerjisi Sisteminde Optimize Edilmiş DVR ile Gerilim Düşüşlerini Azaltma

Öz

Elektrik şebekelerinde en ciddi güç kalitesi problemlerinden biri gerilim düşüşleridir. DVR, bu güç kalitesi problemlerinin çözümünde kullanılan yaygın özel güç cihazları olarak bilinmektedir. Bu çalışmada, şebeke gerilim kesintileri, gerilim düşmeleri ve gerilim yükselmelerinin hızlı ve güvenilir bir şekilde tespiti için rüzgar enerjisi sistemi altındaki DVR'nin kontrol devresinde WCA algoritması ile optimizasyon yapılmış, performansları geleneksel PI kontrolöre göre değerlendirilmiştir. Bu kontrol yöntemleri, şebeke geriliminin genlik ve faz bilgilerini anlık olarak çıkararak gerilim değişikliklerini hızlı ve doğru bir şekilde tespit edebilir ve bu bilgiler yardımıyla, bağlantı noktasına enjekte edilmesi gereken voltaj elde edilebilir. Simülasyon çalışmasında, DFIG tabanlı rüzgar enerjisi sisteminde DVR tarafından üretilen ve sisteme enjekte edilen gerilimler de bu iki farklı kontrol yöntemi kullanılarak sunulmuştur.
WCA tabanlı PI denetleyicinin üstünlüğü sonuçlarda açıkça görülmektedir.

Anahtar Kelimeler: Gerilim düşüşlerini azaltma, Su döngüsü algoritması, DFIG tabanlı rüzgar sistemi, Optimizasyon

* Corresponding Author: halebakir@cumhuriyet.edu.tr

1. Introduction

Changes in the amplitude, frequency and waveform of the voltage and current that cause damage or malfunction of the equipment and end-user loads connected to the electrical power system are defined as electrical power quality problems. Voltage drop and voltage rise are the most common electrical power quality problems encountered in electricity distribution systems. Power electronics based compensation devices have been developed to solve voltage drop and voltage rise problems in electricity distribution systems and end user loads. These; Uninterruptible Power Supply, static transfer switch and Dynamic Voltage Restorer (DVR).

The most effective system developed for compensation of voltage drop and voltage rise is the DVR. In DVR, the voltage amplitude and phase information should be determined in the most accurate and fastest way in order to keep the voltage constant in cases where voltage drops and rises occur.

In (Patel, Goswami, & Singh, 2015), proposed technique, based on half-cycle averaging, can mitigate voltage sag at desired locations in distribution systems.

The proposed methodology is applied in a 4 bus system and a real Indian distribution system. In (Tarek, Abdel-Mon'em, Mahmoud, & Amr, 2010), with induction motors loads with inherit inertia, the proposed DVR would be of lower cost, simpler controller and faster response. In (Praveena, 2014), during the different fault conditions like voltage sag ,single line to ground ,double line to ground faults, PI controller and discrete PWM pulse generator are used for the control purpose.

In (Balasubramanian, 2016), it introduces the terminology and various issues related to 'power quality. This problem can be mitigated with voltage injection method using custom power device called 'Dynamic Voltage Restorer' (DVR). In (Sachin Y. S. , 2014), it is the study of Dynamic Voltage Restorer (DVR) which is the most efficient and effective device to protect sensitive equipment against voltage sags,In based PI with Fuzzy Logic Controller using MATLAB/SIMULINK software. In (Pandu & Nagappan, 2015), it is proposed three PI(method and also by Simple Particle Swarm Optimization based PI method and also by Simple Particle Swarm Optimization based PI controlled DVR.

In (Du et al., 2019) , an optimization compensation controlled DVR. An optimization compensation strategy is based on externality theory and the simulation on compensation strategy is tested on the MATLAB/Simulink. controller method and obtained results are compared with the Proportional-Integral (Gandoman et al.) controller tuned by Ziegler-Nichols strategy is based on externality theory and the simulation on compensation strategy is tested on the MATLAB/Simulink. (Khanh, 2019), it uses the IEEE 33-buses distribution feeder as the test system for voltage sag simulation and influential parameters. In (Arya, Maurya, & Naidu, 2018), The whale optimization Algorithm (WOA) provides the appropriate values of proportional integration (Gandoman et al.) for DVR and voltage sag mitigation and controller's gains within less time as compared to manual tuning of PI controller. In (Jamshidi, Ghahderijani, & Barakati, 2012), it is proposed the issue of application and analysis of a Dynamic Voltage

Restorer (DVR) to enhance the quality of power flows in a stand-alone micro-grid, including wind energy conversion systems. In (Amalorpavaraj, Kaliannan, Padmanaban, Subramaniam, & Ramachandaramurthy, 2017), for voltage sag mitigation capability, active and reactive power support, dc-link voltage balancing, combined control is verified through MATLAB/Simulink-based simulation results using a 1.5-MW grid connected doubly fed induction generator based wind turbine (DFIG-WT). In (Ann Jerin, Kaliannan, Subramaniam, & Thirumoorthy, 2016), wind farm field data of the voltage sag and swell events during fault conditions are re-created using MATLAB/Simulink and restored by employing the DVR. In (Gandoman et al., 2018), DVR is capable of providing fast voltage sag mitigation during faults and can maintain the nominal operating conditions for DFIG-WT.

The aim of this study is to analyze the different methods used in the simulation environment for the determination of the change in voltage sag mitigation using optimized DVR for DFIG-WT. It is the determination of the best method according to the performance criteria.

Adjustment of PI gain constants in the DVR is done automatically based on conventional and WCA to get a good response. A study of tuning and optimization of methods of DVR optimized using WCA in DFIG-WT for voltage stability has not been published in literature. WCA is one of the most preferred optimization techniques in error minimization, cost minimization problems.

2. Method

2.1. Wind energy system modeling

Double Feed Induction Generator (DFIG) based wind generators are among the most preferred.DFIG consists of stator windings and rotor windings arranged in a back-to-back voltage-based converter with fixed frequency and directly connected to a 3-phase grid. Converters transmit current at different frequencies to the rotor to adjust the mechanical and electrical frequency.Generator behavior is organized by power converters or controllers under normal operating or fault conditions.(Abad, 2011).

DFIG is consists of cascading voltage source converters based on connection to a fix frequency three-phase grid and bidirectional connection of windings to the rotor. Basically, on the rotor side, the rectifier controls the rotor current components while regulating the active-reactive powers.On the other hand, the inverter on the grid part keeps the DC bus voltage under control. (Bakir & Kulaksiz, 2019).

In the DFIG system, it has the advantage of being able to control the rotor current and active and reactive power (Abad, 2011). The control circuit in Fig. 1 includes two sequential converters, rotor-part control and upstream-part control. The upstream control circuit of the wind three-phase current component *(Ia, Ib, Ic)* of the wind, *Vbus* (grid voltage), Q (component of reactive power), is taken into account in the grid part control circuit. *Id&Iq* and *Vbus* are regulated and controlled.

Space transforms vector are used to convert voltage components (*Vd&Vq*), current components (Iq&Id) into three-phase signals. Phase Locked Loop (PLL) determines the angles

based on the voltage values, and then the study is performed by using it in space vector according to Park and Clarke transformation.
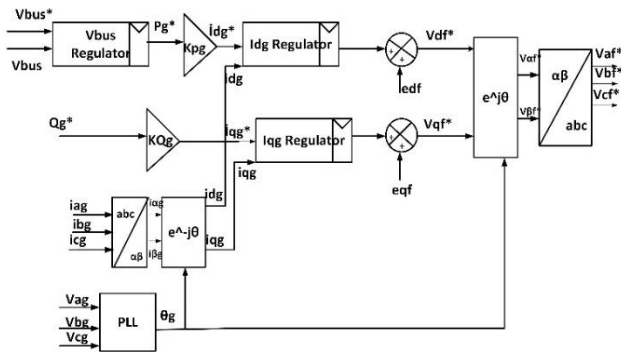

Fig. 1. Grid side control circuit

Control circuit is drawn in Simulink environment. The aerodynamic model is based on calculating rotor power by calculating a torque with airflow through the blades. Wind speed (Vw) can be thought of average speed over an swepting area by the blades.

The wind turbine produced power equation is shown in Eq. (1).

$$P_w = \frac{1}{2} C_p \rho A V_w{}^3, \tag{1}$$

The aerodynamic torque's amount given in Nm is shown in Eq. (2).

$$T_t = \frac{1}{2} \rho R^3 V_w{}^2 C_t \ , \tag{2}$$

A wind turbine model was realized by adhering to these power-torque equations. Indirect speed control modeling is preferred for the maximum power point. Some parameters have been determined for the Double Feed Induction Machine and a DFIG model has been created. (Abad, 2011).
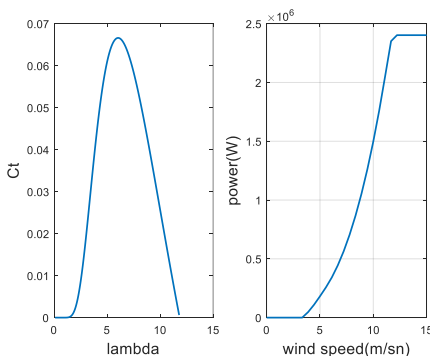

Fig. 2. (a) λ-Ct curve of wind turbine (b) Velocity- Power (v-P) curve for wind

3. Dynamic Voltage Restorer (DVR)

DVR, which is the most suitable system in terms of performance / cost for the solution of voltage drops, is shown in Fig. 3 (Balasubramanian, 2016).

Conventional DVR structure, as seen in the figure, the electrical power system is connected in series with a transformer between the mains and the load.

The power circuit of DVR is basically with voltage-induced inverter. Direct current (DC) consists of energy source. During the voltage drops in the power system, the voltage required to keep the load voltage of the DVR controller is determined and this voltage is created with the DA energy source and inverter. The voltage generated by the transformer is transferred to the electrical power system and the load voltage is kept constant. This prevents the load from being affected by voltage drops. In case of voltage fluctuations in electrical networks, power quality problems need to be compensated as quickly as possible.

In this study, WCA based DVR structure was developed under the Wind energy system to detect voltage variations, fast and accurate detection of problems It is presented an alternative method to detection methods available in the literature.
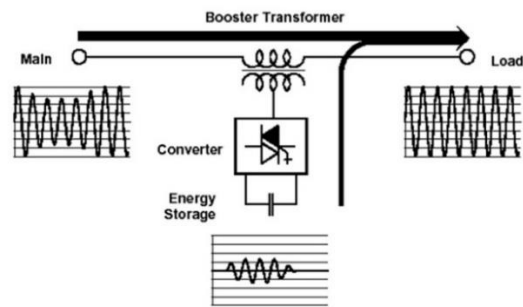

Fig. 3. Conventional DVR structure

Table 1. Parameter Values of DVR model

Parameter	Value
Capacity	1.5 MVA
Filter capacitance	1 μF
Filter inductance	0.1 mH
Switching frequency	10 kHz
Series Transformer	1.5 MVA

The whole shape of the system drawn in Simulink in its environment is given in Figure 4. Rotor-part and grid-part control are aimed with the modeling of a wind turbine-based double-fed asynchronous generator.

By modeling a 1.5 MW DVR system, synchronization control with the PLL has been made to ensure that it works in harmony with the system.
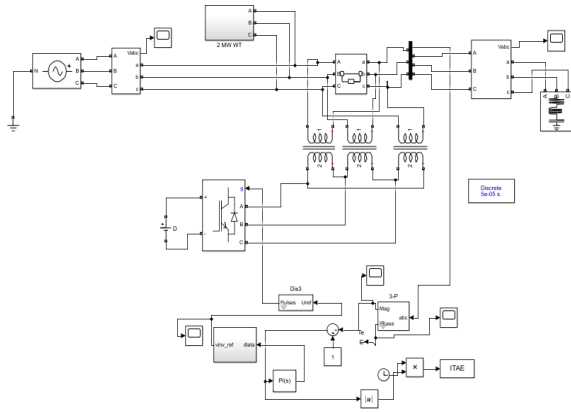

Fig. 4. DFIG based Wind Energy System including DVR

This study aimed to use the time domain criterion to find the optimal values of the PI coefficients in the control circuit of the DVR for voltage stability. According to control system, the gain constants are important, if it takes a troublesome value, it tries to disrupt the characteristics of the system and the system works unstable (Bakir & Kulaksiz, 2019). Optimal adjustment of controller parameters and proper selection of tuning constants have an important role in the proper performance of this control.

Because of this problem, it is important to set the gain constants optimally and choose them correctly.The most used performance criterion has been determined as Integral Absolute Time Error (ITAE). The Integral Absolute Error (IAE) and Integral Square Error have a disadvantage. While the minimization time is better, the transient response is worse.This disadvantage has caused more use of time dependent ITAE or Integral Time Square Error (ITSE) (Bakir & Kulaksiz, 2019). The objective function of the optimization was chosen as the ITAE performance criterion during the study.

4. WCA based method

Fig. 5 is a simplified scheme for a part of the water cycle.

While plants give water during photosynthesis, water in rivers and lakes evaporates. The evaporated water is carried to the atmosphere to form clouds that will condense in the cold atmosphere; this water is released back to the world in the form of rain and precipitation.

Step 1. Make the initial population; It is necessary to construct the values of the question variables as a series. In order to solve an optimization problem using population-based metaphorical methods. This series is called "raindrop" for a single solution in WCA. In optimization problem, a raindrop is a sequence of 1 x N_{var}

This sequence is defined as shown by

$$Raindrop = [x_1, \ x_2,\ ] = [K_p, K_i] \qquad (3)$$

x_1 and x_2 is the parameters which is optimized same K_p and K_i of PI controller gain constants.

To begin the optimization algorithm, a candidate is generated that shows a matrix of raindrops in dimensions N_{pop} x N_{var}. As a result; a randomly generated X matrix appears (line: population number; column: the number for design variables).

$$Raindrops\ population = \begin{bmatrix} Raindrop_1 \\ Raindrop_2 \\ \vdots \\ Raindrop_{N_{pop}} \end{bmatrix} =$$

$$\begin{bmatrix} x_1^1 & \cdots & x_{N_{var}}^1 \\ \vdots & \ddots & \vdots \\ x_1^{N_{pop}} & \cdots & x_{N_{var}}^{N_{pop}} \end{bmatrix} \qquad (4)$$

The decision variable *Fi* can sort continuous and discrete problems as real numbers or a predefined set.The cost of a raindrop is found by calculating the cost function (*F*) As a first step, *Npop* shows raindrops.Portions with the best individuals (minimum values) form *Nsr* seas and rivers.

$$F_i = Cost_i = f(x_1^i, x_2^i, \dots x_{N\_var}^i)\ i = 1,2,3 \dots N_{pop} \qquad (5)$$

where, N_{pop} indicates the number of raindrops in the first population, N_{var} indicates the number of design variables.

As a start, after *Npop* lets raindrops form. The best individuals (minimum values) are selected as the *Nsr* seas and rivers portion.. The rain drop with the smallest value among these selected individuals is considered sea. The remainder of the population forms streams that either flow into rivers or directly flow into the sea (Eskandar, Sadollah, Bahreininejad, & Hamdi, 2012).

$$N_{sr} = \text{Number of Rivers} + 1 \qquad (6)$$

$$N_{Raindrops} = N_{pop} - N_{sr} \qquad (7)$$

It is given by Eq. (8) to transfer it to rivers and the sea, depending on the flow intensity of the raindrop.

$$NS_n = round\left\{ \left| \frac{Cost_n}{\sum_{i=1}^{N_{sr}} Cost_i} \right| xN_{Raindrops} \right\} n = 1,2 \dots N_{sr} \qquad (8)$$

NS_n is the number of streams that will flow into certain rivers and sea.

Step 2. Stream flowing to the rivers or sea;

A stream in Eq. (9) is flows into the river along the connecting line along the river and the given random distance.

$$C > 1 \qquad X \in (0, C \times d), \tag{9}$$

The value for C can be selected as 2. Present between stream and river distance is shown as d.

The value of X in the equation is a distributed random 0-$C \times d$ corresponds to the number.

As a result, the new position stage for rivers and rivers can be given by

$$X_{Stream}^{i+1} = X_{Stream}^i + rand \times C \times (X_{River}^i - X_{Stream}^i) \tag{10}$$
$$X_{River}^{i+1} = X_{River}^i + rand \times C \times (X_{Sea}^i - X_{River}^i) \tag{11}$$

The rand number is a randomly distributed number between 0 and 1.

Step 3. Evaporation condition;

The following code shows river will flow into the sea

$$if \left| X_{Sea}^i - X_{River}^i \right| < d_{max} \, i = 1, 2, \dots . N_{sr} - 1 \tag{12}$$

If the distance between the river and the sea is smaller than max d_{max} (d_{max} is a small number close to 0) indicates that you will reach the sea. In this case, the evaporation process is applied and after enough evaporation rain starts as seen in nature. A small value for d_{max} promotes near-sea search intensity, while a large value reduces near-sea search. Therefore, d_{max} control the intensity of the search near the sea (optimal solution). The value of d_{max} is adjustable decreases by (Sadollah, Eskandar, Lee, Yoo, & Kim, 2016)

$$d_{max}^{i+1} = d_{max}^i - \frac{d_{max}}{\max iteration} \tag{13}$$

Step 4. Sprinkling;

After the evaporation process, it continues with the sprinkling process.

During the sprinkling process, new raindrops form streams in different parts.Eq. (14) is used to create new locations of newly created streams.

$$X_{Stream}^{new} = lb + rand \times (ub - lb) \tag{14}$$

where, *lb* and *ub* are the lower bound and upper bound, respectively.

The parameters *X* are subjected to bound constraints such as

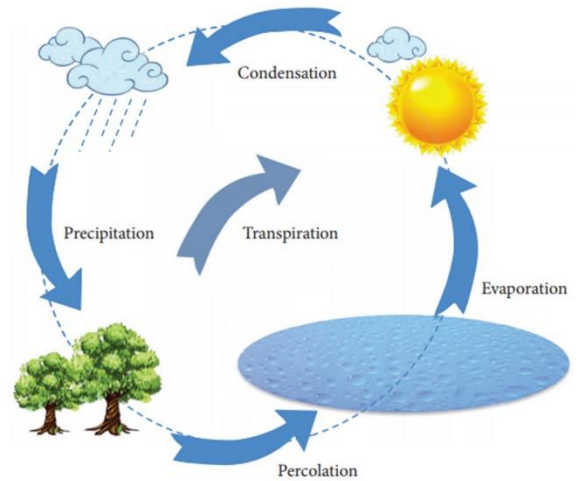$$l_b \le X \le u_b \tag{15}$$

Fig. 5. Water cycle schemes

The formulation objective function is ITAE and optimization performance criterion is called '*F*'. The formula is shown in Eq. 16 for ITAE function.

$$F_{ITAE} = \int_0^T |(error)| \, td(t) \tag{16}$$

T is usually chosen larger than the settling time at the steady-state value of the integral. Errors in the control circuit for the DVR are expressed by the objective function of Eq. 17.

$$OF(X) = w \int_0^T |e_{dc}| td(t) \tag{17}$$

X stands for [***Kp Ki***] and w is the weight factor.

The control circuit of the whole system is shown in Fig. 6. The error value was calculated according to the ITAE formula in Simulink, and then the optimization was carried out according to the ITAE formula.

WCA codes were written considering the M-function code. A good optimization result was obtained by setting the correct restriction, multiplication, mutation and population size values.

The m-function file contains two variables and the optimization is done on two variables in the two-dimensional search space. Certain lower and upper limits are selected. Kp and Ki values are found.
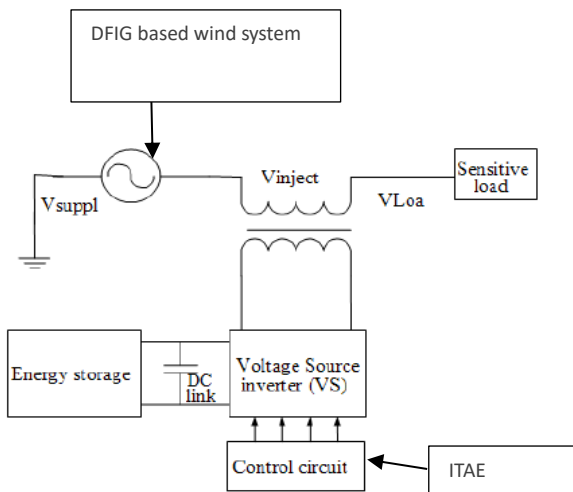
Fig 6. Structure of Whole System for ITAE

Table 2. Optimal parameters in DVR optimized for ITAE

| ITAE	DC regulator	
PI constant	K_p	K_i
Convention al-PI controller	0.1	10
WCA-based PI controller	0.9572	0.0318
GA-based PI controller	0.8588	0.1021

5. Simulation results

The addition of power plants to the grid causes some reductions and deviations in power quality in distribution networks. Renewable sources often cause power quality problems such as slow voltage sag and rapid voltage changes. Voltage fluctuation is one of the most important problems in wind energy systems. The aim is to minimize voltage sag and solve power quality issues with DVR control.

The system firstly operates without DVR incorporation. Fig. 7(a) shows that three-phase voltage profile is decrease and increase. A voltage fluctuation can be seen with the naked eye. When DVR is added in this system, Fig 7(b) shows that three-phase voltage profile is kept constant at 10 kV.

The results show that the correct setting and gain constants selection has an important place in controlling the performance studies of the systems. It is clearly seen in Figure 7(c) that the busbar end voltage value has increased to 1.05 p.u. It drops to 0.98 p.u in 0.025 seconds. It is ensured that the system keeps the voltage fixed at 1.0 p.u. in 0.075 seconds. When the whole result in Figure 7(c) is examined.The results of the two methods are compared in terms of fluctuation and the adjusting system parameters methods as voltage response.
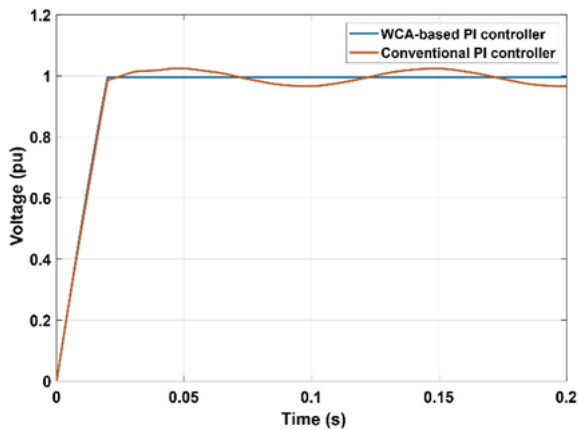
Optimal parameter values of optimization are given in Table 2.
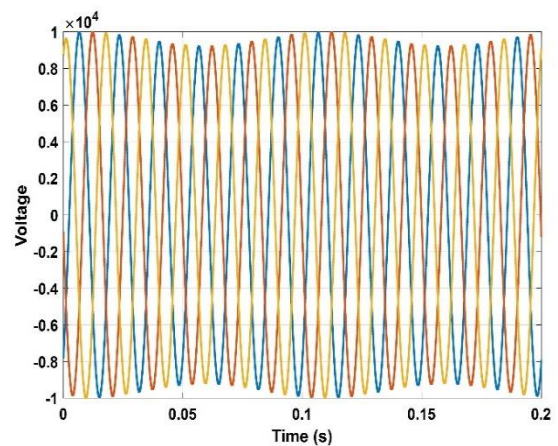
(a)
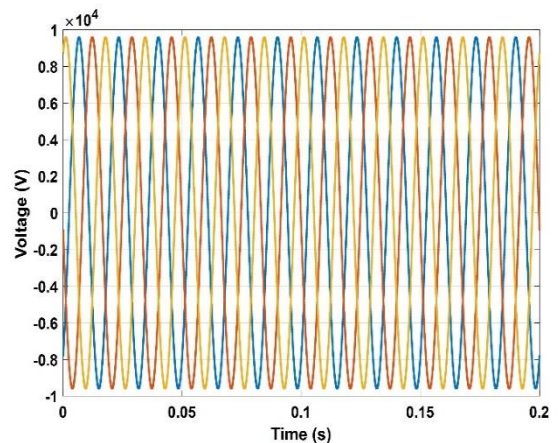
(b)

(c)

Fig. 7. (a) Voltage profile at the load side without DVR, (b) Voltage profile at the load side with DVR (c) voltage profile at load side with conventional- PI controller, WCA optimal controller with DVR (p.u.)

6. Conclusions

A 2 MW wind energy asynchronous generator-based wind generation system and a 1.5 MW dynamic voltage recovery system were modeled and their effects on the grid were examined. It was observed that the DVR reduces the voltage fluctuation through optimal parameters. A wind power system is designed with the addition of DVR. When the output voltage profiles are examined, it is aimed to get good results. WCA-based PI controller is included in the system to examine the voltage profiles. Basically, the study has proven that voltage fluctuation in large transmission systems caused by the inclusion of renewable energy sources in the grid can be reduced and can be minimized and fluctuations

When the results are compared, it is seen that the DVR adjusted with WCA gives more effective results. Voltage fluctuation has been overcome by appropriate adjustment of the PI gain parameters. And a better dynamic response response has been achieved.

For future studies, the study can be enriched by using different optimization techniques and different FACTS devices.

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