Dynamic Voltage Restorer for Mitigation of Voltage Sags Due to 3 Phase Motor Starts Based on Artificial Neural Networks

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ARTICLE INFO

Article history:

Received March 02, 2023
Revised March 21, 2023
Published April 04, 2023

Keywords:

Voltage Sag;
DVR;
ANN;
Induction Motor

ABSTRACT

The Direct On-Line (DOL) process of starting a high-power 3-phase induction motor causes voltage sags in the distribution system that is connected to one point of common coupling (PCC). Voltage sag can cause damage and failure of sensitive loads. This article analyzes and proposes a simulation of voltage sag recovery using a Dynamic Voltage Restorer (DVR) based on an Artificial Neural Network (ANN). ANN is used as a detector and regulator of the voltage compensation value. In this study, a 3-phase induction motor will be connected to a sensitive load, and the DVR will be placed in series with a voltage source or PCC with a sensitive load. The simulation test system uses Simulink-Matlab R2016a with different configurations of induction motor parameters. Based on the simulation results show that the parameters of the 3-phase induction motor cause the depth and duration of the voltage sag. DVR with ANN control can detect and compensate for a voltage sag of 0.5 pu so that the voltage will be normal to 1 pu.

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1. INTRODUCTION

Currently, the use of electric motors with large power capacities in the industry has become a necessity to speed up the production process [1]. When starting the motor which is connected directly on line (DOL) with large power, it will require a large starting current of 8 to 10 times the nominal current to obtain sufficient starting torque to rotate the motor [2]. The existence of a high starting current in the electric power system will cause voltage sag in the network that is connected to one system [3], [4]. Apart from starting the motor, voltage sag can also occur due to disturbances in the power system, large starting loads, transformer taping, short circuit faults, and recloser closures [5], [6]. Disturbances that occur in distribution channels will not only have an impact on distribution channels that are disturbed but will have an impact on other distribution channels that are connected to the same PCC [7].

Voltage sag is a decrease in the RMS voltage of 10% to 90% of the operating voltage which lasts for 0.5 cycles up to 1 minute [8]. The voltage sag can cause operation failure even to the point of damage to some electrical consumer equipment which is sensitive to changes in voltage in a short time [9], [10]. The failure of electrical equipment in some industrial consumers will experience blackouts so that production will stop which causes economic losses [11]. Equipment that is sensitive to voltage sags, namely relays, contactors, electronic equipment, PLCs, and computers [12], [13]. Voltage sag characteristics can be seen in Fig. 1.

Voltage sag can be mitigated using Custom Power Device (CPD). Custom Power Device (CPD) that can mitigate voltage sags such as D-STATCOM [14], SVC, UPFC, UPS, and DVR [15], [16]. Of the several CPD equipment, the DVR has the advantage that it has installed energy storage so that maintenance costs are lower than UPS and SMEs, the size of the DVR is smaller than D-STATCOM, and the DVR can also improve the power factor and minimize harmonics [17], [18]. The DVR circuit is connected and installed in series between the PCC and the sensitive load to maintain the quality of the voltage at the load [19]. In the event of a voltage sag, the DVR system will detect a voltage sag so that the DVR will inject voltage compensation [20]. Detection of voltage sag on the DVR requires a control system that is fast and accurate [21]. The control method chosen is Artificial Neural Network (ANN) in detecting and regulating the voltage compensation value. ANN has advantages in terms of speed and accuracy of voltage compensation [22], [23].

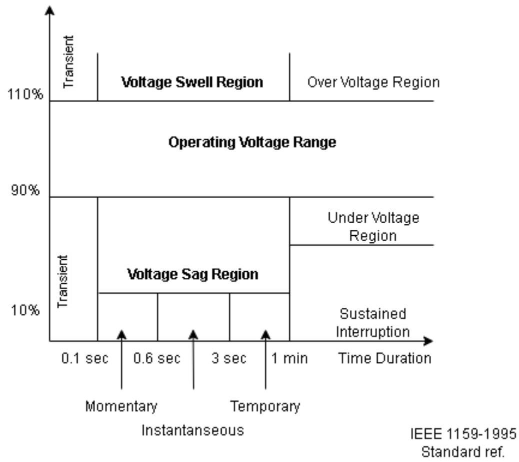

Fig. 1. IEEE std 1159-1995, Voltage Sag Characteristic

ANN is formed by imitating neural networks in humans that are connected to provide information from sensor detection results to be processed to obtain output results [11], [24]. ANN consists of input data, adding weights, processing, and output [25], [26]. To get the appropriate output, ANN needs to be trained [27]. In a DVR control system that uses ANN, an ANN model has problems with training data that includes various drop conditions [28]. In this study, ANN was trained using the backpropagation method and Levenberg Marquardt optimization based on error data and appropriate actions. The main contribution of mitigating voltage sag using ANN-based DVRs is increasing the reliability and quality of power in the electrical system. By preventing or overcoming voltage drops, you can avoid disturbances to electrical equipment and increase the efficiency of using electrical energy. Section 2 describes the design and block system on dynamic voltage restorer. Section 3 describes modeling using the ANN method on the DVR, and Section 4 present and review research findings.

2. DESIGN DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer (DVR) is one of the power electronics equipment that is used to protect sensitive equipment against voltage changes due to voltage sag [29]. The working principle of the DVR is to inject dynamic voltage in a controlled manner into the bus experiencing voltage sag disturbances [30]. The DVR is connected in series between the voltage source and the sensitive load which is used to reduce sag and swell problems in the load section. The basic components of the DVR are the DC voltage source, Voltage Source Inverter (VSI), control system, filter, and voltage injection transformer [31] is shown in Fig. 2. The schematic structure of the DVR is shown in Fig. 3.

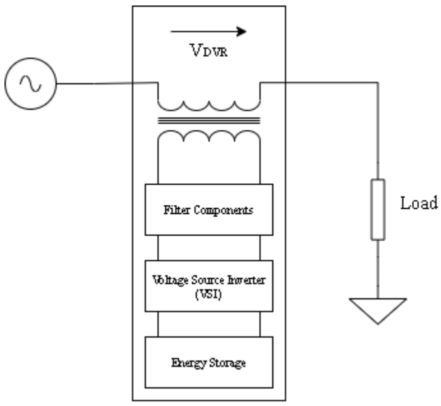

Fig. 2. Basic Block Diagram of DVR

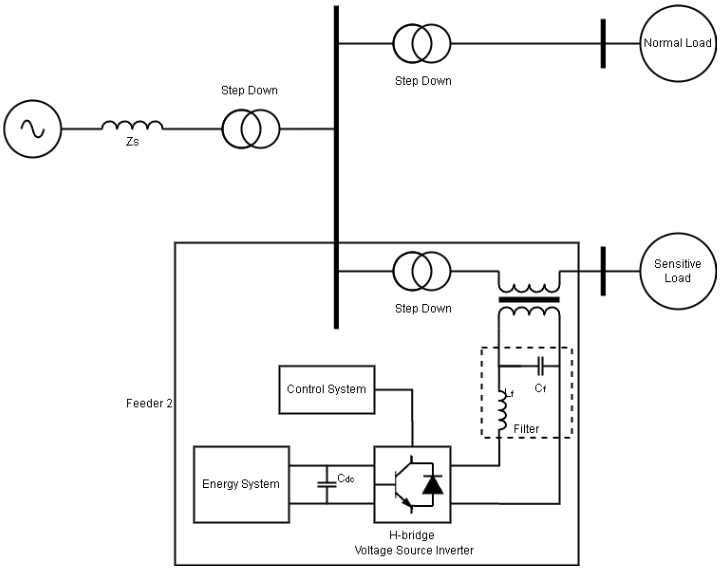

Fig. 3. Structure of DVR

2.1. Voltage Source Inverter (VSI)

VSI is used to convert DC voltage from energy storage to AC voltage which is later needed by the injection transformer [32]. VSI consists of switching equipment that can generate a sinusoidal voltage at the required frequency and phase angle. This study uses switching with 6 IGBT pulse switches in the form of PWM pulses.

2.2. Control System

The use and selection of a control system are important, provided that it has a fast and precise response to the voltage sag detection process and various changes in the connected load power [33]. There are many uses of the control system other than as a voltage sag detector, namely as a converter of the voltage sag value into a dq0 signal using a park transformation, setting the voltage injection value, and generating a signal for the PWM inverter.

2.3. Filters

The filter is installed after the VSI which is used to prevent the harmonic order generated by the VSI device somewhat from passing through the injection transformer coils [34]. This filter works by eliminating high frequencies along with the switching inverter.

2.4. Injection Transformer

The main function of the injection transformer is to increase the AC voltage from VSI to the system according to the voltage needed by the system when there is a voltage sag [35]. Apart from being a voltage injector, this transformer can be used as a coupling and protection that connects the DVR to the distribution network through the transformer's primary winding. It can also reduce noise coupling and transients that occur in the primary winding to the secondary winding of the transformer.

3. ANN CONTROL SYSTEM ON DVR

The ANN process as a control on the DVR is illustrated through the flow diagram in Fig. 4 ANN algorithm process. The initial steps taken were to identify the data voltages that experienced sag, then proceeded to the feature selection process and refined the training data and testing sets. Then it is evaluated as a performance indicator of the ANN algorithm.

In this study, ANN control is used which functions as a determinant of the value of load compensation based on real-time voltage sag detection according to the maximum load voltage requirement [36]. The detection of voltage sag measurements in the RST/abc phase will be converted to dq0 coordinates using the park transformation [37]. The park transformation produces the form dq0 which represents the form d is the depth of the voltage sag or swell voltage that occurs, and the q form means the phase shift when the disturbance occurs. Based on the results of the park transformation, the values of d and q will be compared with the reference d value, which is 1 (actual voltage value is 1 pu) and the reference q value is 0 (actual phase difference value is 0). The ANN training design model is shown in Fig. 5.

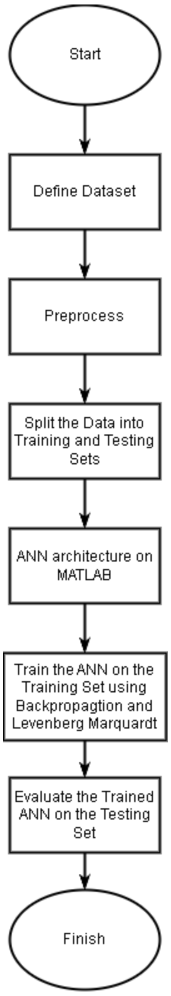

Fig. 4 Flowchart ANN Processing

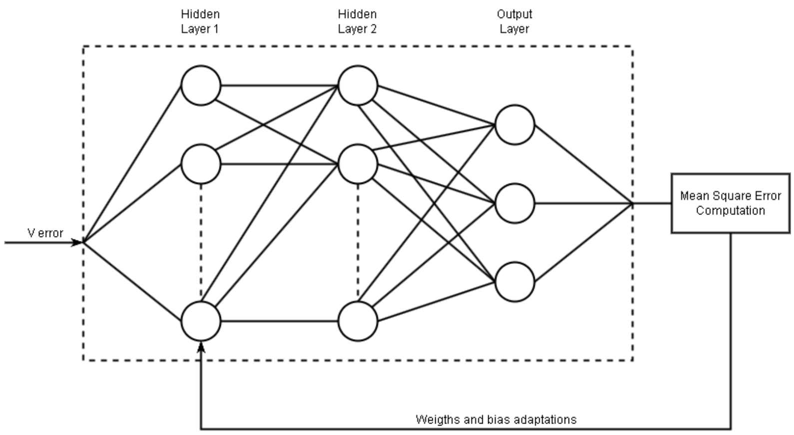

Fig. 5. ANN Training Plan

To maintain the phase of the output voltage to be the same as the source voltage, a Phase Locked Loop (PLL) circuit is used. The PLL function is used to derive the values of the vector $sin\ 0$ and $cos\ 0$. The mathematical calculations for the park transformation are shown in the following (1)-(3) [38], [39].

$$Vd = 2/3(Va\, sin(\omega t) + Vb\, sin(\omega t - 2\pi/3) + Vc\, sin(\omega t + 2\pi/3)) \quad (1)$$

$$Vq = 2/3(Vacos(\omega t) + Vb\, cos(\omega t - 2\pi/3) + Vc\, cos(\omega t + 2\pi/3)) \quad (2)$$

$$V0 = 1/3(Va + Vb + Vc) \quad (3)$$

Based on Fig. 4, the system input data process stage is divided into two sub-subs, namely the first sub consisting of 70% of the data which functions for ANN training and the second sub consisting of 30% which functions as testing and validation. The ANN model structure consists of 2 inputs, 10 hidden layers, and 1 output where the training algorithm uses Levenberg-Marquardt. The training process is carried out by setting the appropriate input or output mode for training, with the adaptation of the weight value. The value of the weight before training will be random, so after training the weight will be worth it. For each ANN training pattern, the network will imitate the input information data to get the expected output according to the training pattern. The error value is compared to the maximum error tolerance or MSE, and if it exceeds the threshold, the system is adjusted accordingly [40].

The error value comparison is used to determine the voltage compensation value. The error signal obtained will be converted from the form dq0 to an abc signal. Mathematical calculations on the inverse park transformation are shown in the following (4)-(6) [39].

$$Va = Vd\, sin(\omega t) + Vq\, cos(\omega t) + V0 \quad (4)$$

$$Vb = Vd\, sin(\omega t - 2\pi/3) + Vq\, cos(\omega t - 2\pi/3) + V0 \quad (5)$$

$$Vc = Vd\, sin(\omega t + 2\pi/3) + Vq\, cos(\omega t + 2\pi/3) + V0 \quad (6)$$

The results of the training based on the MSE value on the d value can be seen in Fig. 6 and on the q value in Fig. 7.

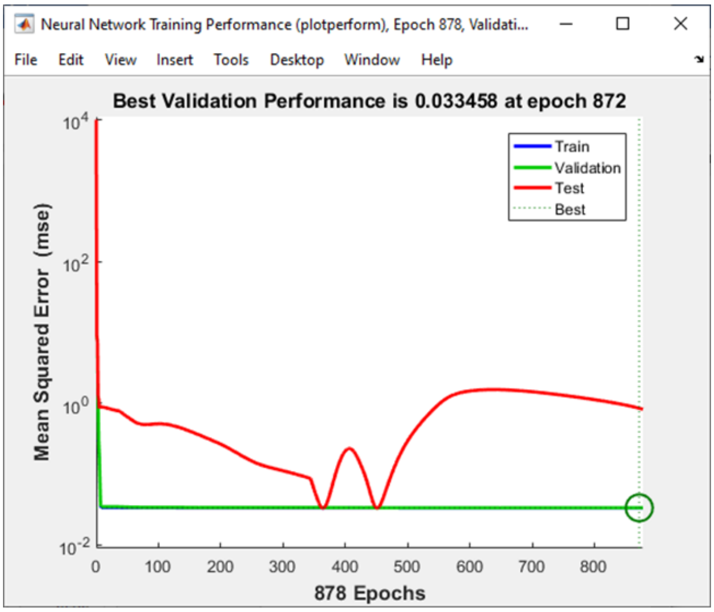

Fig. 6. Meansquare Error Valuer of ANN Training on Input d

The results of ANN training on input d obtained MSE results of 0.033458 on the epoch value or dataset that went through the training data process of 872. So, the results of ANN training on input d are interpreted as error detection processes will be worth less than 3.34%. For input q, the MSE value is 0.0052597 at an epoch value of 580. So, the results of ANN training on input q are interpreted as errors in the detection process which will be worth less than 0.52597%. The smaller the MSE value, the better the ANN training process will be.

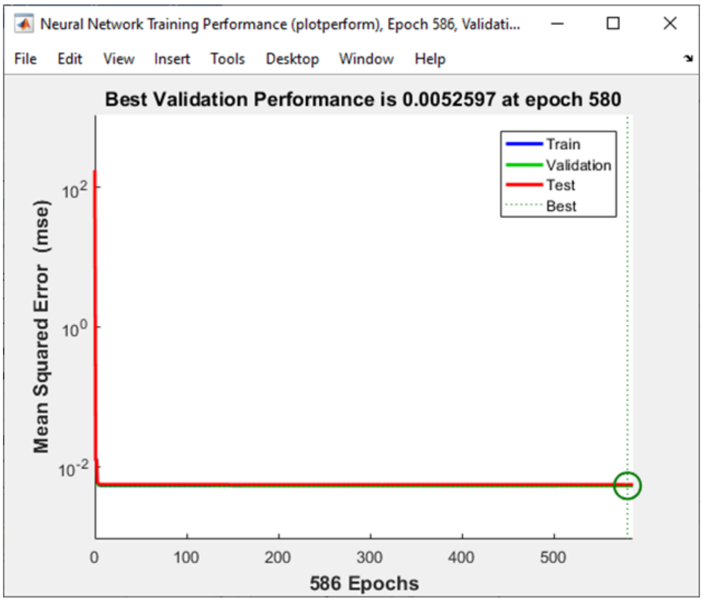

Fig. 7. MeanSquare Error Value of ANN Training on Input d

4. RESULTS AND DISCUSSION

Recovery of voltage sag due to motor starting using DVR with ANN control system on a 20 kV distribution system will be simulated using Simulink MATLAB 2016a software. The system voltage sag recovery simulation can be seen in Fig. 8. The main component parameters are shown in Table 1.

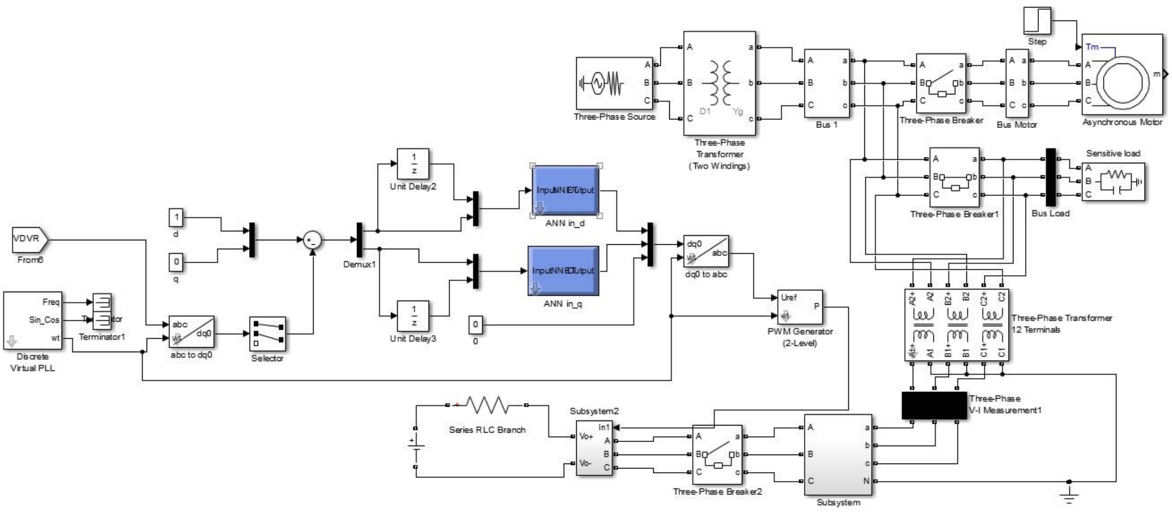

Fig. 8. Modelling DVR on Simulink

Table 1. Distribution System and DVR Parameter

Parameters	Rating
Three phase sources	60 MVA, 150kV
Distribution transformer step-down	150/20 kV
Fundamental frequency	50 Hz
DC Voltage Source	2 kV
Injection Transformer	1/20kV, 50Hz, 30 MVA

The injection of voltage sag using a DVR caused by the impact of starting a 3-phase induction motor is simulated in the Simulink-MATLAB R2016a application. Based on Fig. 3, a 150kV 3-phase voltage source is connected to a step-down transformer to 20 kV which is connected to two loads, namely the motor load and the sensitive load protected by the DVR. The factor causing the voltage sag is done when the 3-phase induction motor is starting. The motor starting process is carried out in the simulation at 0.2 seconds so that it can be seen the effect of voltage sag in the connected distribution system.

In this simulation, a test will be carried out with two different use cases of a 3-phase induction motor. The value of the 3-phase induction motor will be changed to see the voltage sag disturbance that occurs and the DVR's response to injecting the voltage when the voltage sag occurs.

4.1. Case 1

In the first simulation, the scenario sees how much the induction motor causes voltage sag in the distribution system. To find out, the induction motor parameters will be made as in Table 2.

Table 2. Parameters of Induction Motor in the First Scenario

Parameters	Rating
Asynchronous motor general ratings	60 MVA, 150kV
Motor stator resistance	0.7384
Motor stator inductance	0.00304
Motor rotor resistance	0.7402
Motor rotor inductance	0.00304
Mutual inductance	0.1241

Induction motors have parameters of rotor resistance (Rr), stator resistance (Rs), rotor inductance (Lr), stator inductance (Ls), and mutual inductance (Lm). The magnitude of the values contained in some of these parameters will affect the magnitude of the voltage sag that occurs. The waveform of voltage sag due to starting a 3-phase induction motor and voltage recovery using a DVR is shown in Fig. 9, Fig. 10, and Fig. 11.

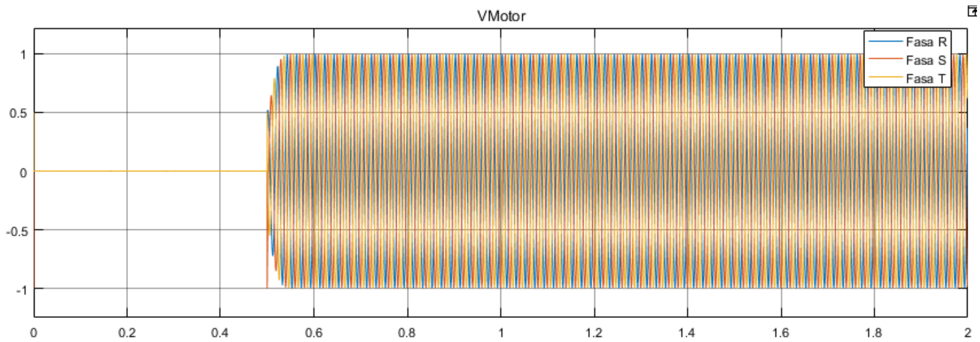

Fig. 9. the Motor Voltage Waveform During the Starting Process

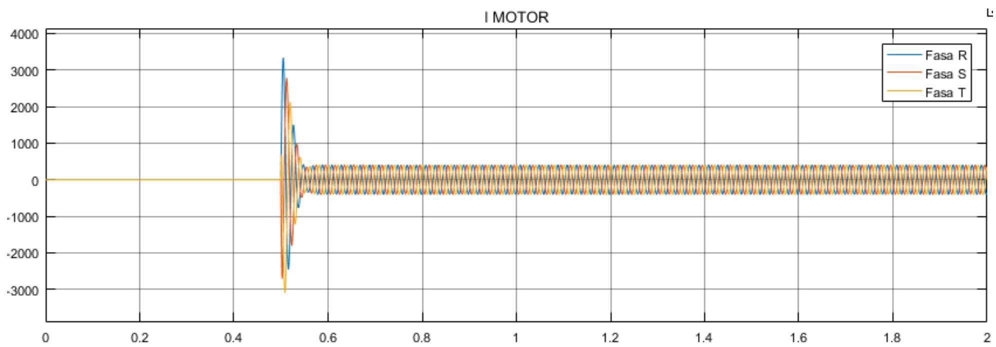

Fig. 10. Current Wave During the Induction Motor Starting Process

Based on Fig. 9 is the induction motor voltage wave in the DOL starting process. The voltage decreased at the beginning of the starting seconds, which was 0.5 seconds by 0.4 pu. The voltage sag is caused by an increase in the induction motor starting current during the starting process at 0.5 seconds as shown in Fig. 10. The voltage on the induction motor returns to normal from 0.4 to 1 pu for 0.05 seconds. The voltage sag in the induction motor causes a voltage sag in the sensitive load connected to the same PCC.

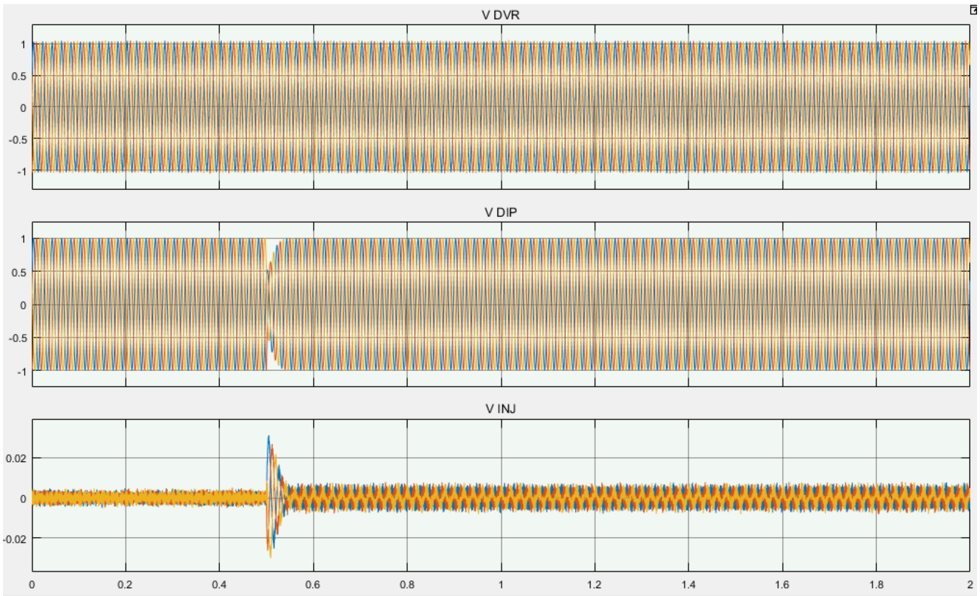

Fig. 11. Wave After Mitigation Voltage Sag, Voltage Sag, and DVR Injection

The voltage sag that occurs in a sensitive load is shown in Fig. 11. Vsag is a voltage sag that occurs when the 3-phase induction motor starting process is carried out at 0.5 seconds. The voltage in the load-sensitive network has decreased from 1 pu to 0.4 pu. The DVR control system, namely ANN, will detect a voltage sag that occurs so that the DVR will inject the V INJ voltage which is the DVR injection voltage into the system that experiences a voltage sag at 0.5 seconds through the injection transformer. V DVR is a voltage wave after injection, and it looks like the wave is normal again to 1 pu.

4.2. Case 2

In the second simulation scenario, the motor power and parameters of stator resistance, stator inductance, rotor resistance, rotor inductance, and mutual inductance contained in the induction motor will be changed. Parameters on the induction motor are shown in Table 3.

Table 3. Parameters of Induction Motor in the Second Scenario

Parameters	Rating
Asynchronous motor general ratings	60 MVA, 150kV
Motor stator resistance	0.7384
Motor stator inductance	0.00304
Motor rotor resistance	0.007402
Motor rotor inductance	0.00304
Mutual inductance	0.1241

The parameters on the induction motor will affect how long and how big the sag in voltage sags in a distribution network that is integrated with one Point of Common Coupling (PCC). The waveform of voltage sag due to starting a 3-phase induction motor and voltage recovery using a DVR is shown in Fig. 13, Fig. 14, and Fig. 15.

Fig. 13 shows the induction motor voltage waveform in the DOL starting process. The voltage decreased at the beginning of the starting which is 0.5 seconds by 0.4 pu. The decrease in voltage is caused by an increase in the starting current of the induction motor during the starting process at 0.5 seconds as shown in Fig. 14. The voltage on the induction motor returns to normal from 0.5 to 1 pu for 3 seconds. The voltage sag in the induction motor causes a voltage sag in the sensitive load connected to the same PCC.

The voltage sag that occurs in a sensitive load is shown in Fig. 15. V SAG is a voltage sag that occurs when the 3-phase induction motor is started at 0.5 seconds. The voltage in the load-sensitive network has decreased from 1 pu to 0.5 pu. The DVR control system, namely ANN, will detect a voltage sag that occurs so that the DVR will inject the V INJ voltage which is the DVR injection voltage into the system that experiences a voltage sag at 0.5 seconds through the injection transformer. V DVR is a voltage wave after injection, and it looks like the wave is normal again to 1 pu. Based on research [41], compensation for the sag voltage when using ANN when there is a load produces an average compensation of 1.4 pu, which exceeds the normal voltage threshold of 1 pu, so that in this study it shows that the ANN model used for the DVR system is appropriate.

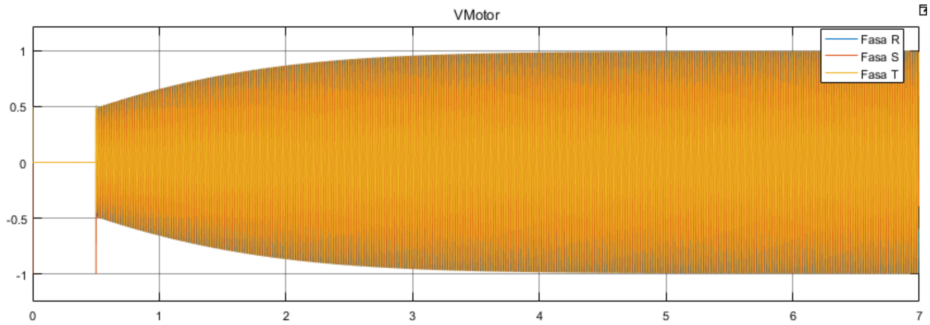

Fig. 12. the Motor Voltage Waveform during the Starting Process

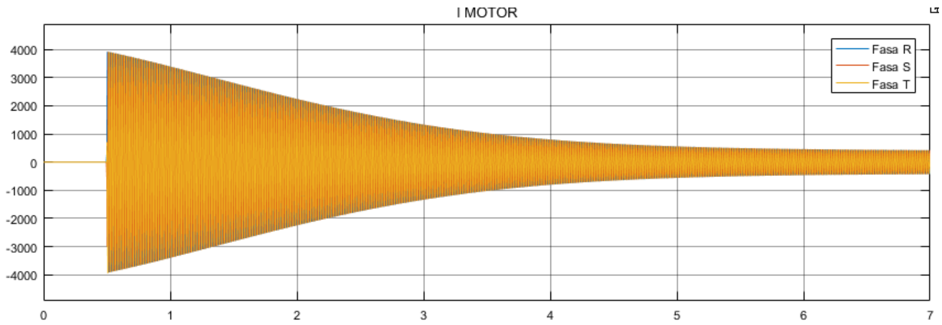

Fig. 13. Current Wave during the Induction Motor Starting Process

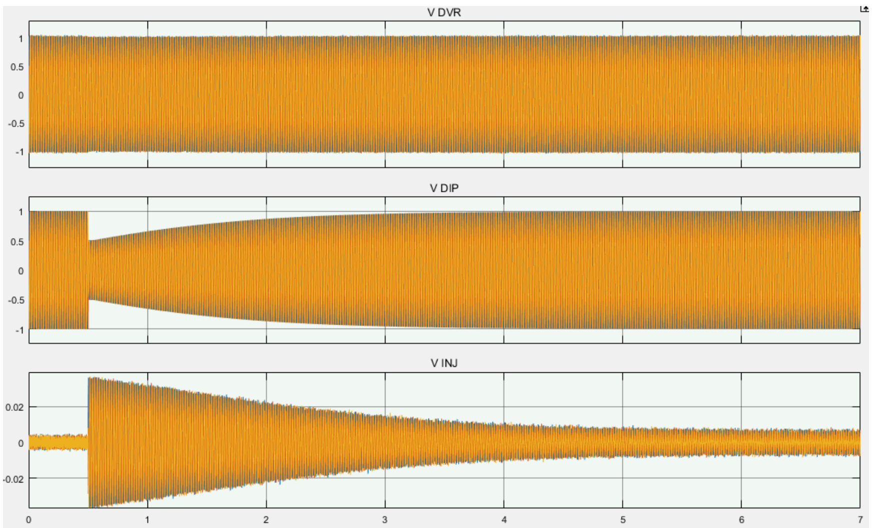

Fig. 14. the Motor Voltage Waveform during the Starting Process

5. CONCLUSION

The Direct-On Line (DOL) process of starting a high-power 3-phase induction motor causes a voltage sag. In this article, voltage sags are simulated with two-parameter scenarios of induction motors that cause voltage sags. The simulation results show that in the first induction motor scenario, there is a voltage sag on the sensitive load side of 0.4 pu for 0.05 seconds and in the second scenario occurs a voltage sag of 0.5 pu for 3 seconds. The DVR detects a voltage sag, so the ANN control system will determine the amount and time of DVR injection. The DVR will convert the DC voltage into AC voltage to be injected through the injection transformer. The voltage sag can be mitigated by the DVR and the voltage at the sensitive load returns to normal. In this research carried out on a 3-phase induction motor load test, which is assumed to be the readiness of the application of the ANN model in DVR optimization in repairing dip and swell voltages. Future research can increase coverage, for example in PLN and Industrial distribution networks. Furthermore, the ANN model can be improved with other combinations or hybrids, and the impact of power flow can be investigated further.

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