Design of Novel Approach to Mitigate Voltage Sag Caused by Starting an Induction Motor Using Dynamic Voltage Restorer

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ABSTRACT:
In this paper, a new control strategy for dynamic voltage restorer (DVR) is presented to compensate effectively voltage sags. In this strategy, load and supply voltage magnitude and angle are estimated by least error square filters in short time. The advantage of this method is reducing noise, distortion, and harmonic on estimation parameters. Accordingly, these parameters are controlled for each phase separately. Also, it should be noted that due to the phase angle estimation by LES filters, the control system does not require phase-locked Loop and this issue causes an increase in speed of control system response. In addition, a P+Resonant and Posicast controller are used to eliminate the steady-state error and improve transient response in DVR, respectively. The proposed control system is simulated, using PSCAD/EMTDC software by induction motors starting is connected to 13 bus IEEE standard network. Finally, the simulation results prove that the proposed control scheme performs satisfactorily under sudden changes of load.

KEYWORDS: Dynamic voltage restorer, Voltage sag, Least error squares filters, Control system, Power quality.

1. INTRODUCTION

Nowadays, due to increasing in electronic devices and equipment that are sensitive to power quality, the necessity of appropriate equipment in order to supply proper power quality for the customer is sensed [1], [2]. Voltage sag is a typical problem of power quality for sensitive loads [3], [4]. If the voltage sag is increased two or three cycles, it may cause great loss [5]. According to IEEE standard, voltage sag is a reduction of voltage from 0.1 to 0.9 pu. of its rms value, having a duration of half a cycle to one minute [6]. Short circuit, starting big motors, sudden changes in load and transformer energizing can be considered as main causes of voltage sag [7]. Until now, many methods have proposed for voltage sag compensation. Using DVR in order to improve power quality and compensation of load voltage is one of them [8], [9]. DVR is a power electronic based device and its main structure is composed of a three-phase voltage source inverter. The operation of DVR is in a way that it keeps the voltage of a sensitive load in appropriate range by injecting a three-phase voltage in series with supply [10]. As presented in Fig. 1, DVR consists of an

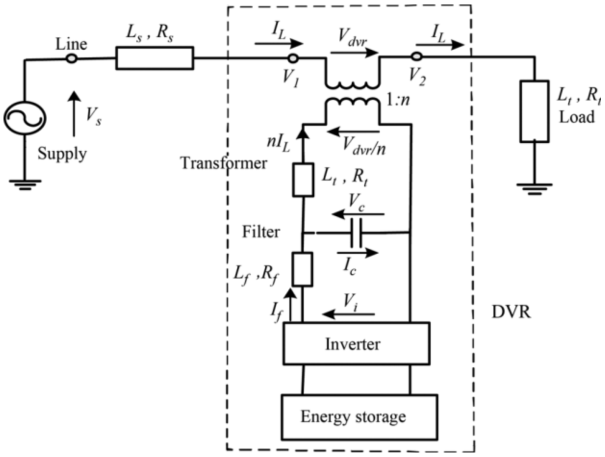

Fig. 1. Schematic diagram of the DVR.

Injecting transformer which is connected to the network in series, a voltage source inverter, a harmonic filter and an energy saving device [3], [11].

There are different proposed plans for voltage sag compensation by DVR. Most of them, make us of DVR control techniques including Phase-Locked Loop (PLL) [12] or Kalman filters [13], [14] or complex Fourier transformation [15] that are used to estimate phasor parameters and control them as well. Because of having a half cycle delay, these methods compensate voltage sag with a delay [16].

Considering the deficiencies of the former methods, this paper proposes a comprehensive and fast control method for the DVR. In this method, The phasor parameters (magnitude and angle) of the measured supply and load voltages are estimated by using least error squares (LES) filters [16-19] in a short time (5 ms). In addition to fast and reliable estimation of phasor parameters, LES filters reduce effects of noise, distortion, and harmonics on estimated parameters. The proposed multi-loop control system [20-24] includes a load voltage control system and an injected voltage control system. The load voltage control system controls phase angle and magnitude of load voltage in order to restore it to presag conditions. On the other hand, the injected voltage control system includes a P+Resonant controller and a Posicast controller [24], [25], [26].

The Posicast controller is a function with two parts and is used to improve the damping of the transient oscillations at the start instant from voltage sag. The P+Resonant controller includes a proportional function and a resonant function and it is used to eliminate the steady-state error [24], [27].

Advantages of the proposed control system include using LES estimation filters, void of PLL and using simple integrator and proportional controllers. The efficiency of proposed control scheme is evaluated using simulation studies in PSCAD/EMTDC software.

2. PROPOSED CONTROL METHOD

In this part, DVR control system is presented. Assume that the load and supply voltage fundamental frequency components, the following equation can be defined

$$v_s = V_s \times \cos(\omega t + \theta) \qquad (1)$$

$$v_l = V_l \times \cos(\omega t + \theta). \qquad (2)$$

As Fig. 2 shows, two LES filters are used in order to estimate magnitude and phase angle of load and supply voltage [16]. In LES filter estimation method, if:

$$v = V \times \cos(\omega t + \theta) \qquad (3)$$

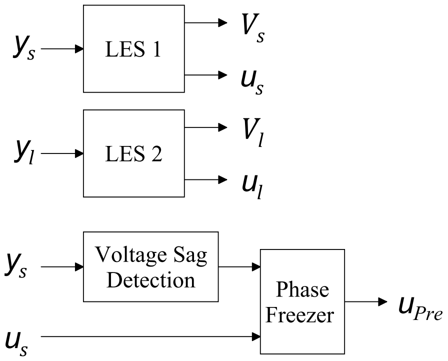

Fig. 2. Phasor parameter estimation

Where *D*t is sampling period, N is the number of samples and $[A]^{LPI}$ stands for left pseudoinverse matrix of [A] and

$$\begin{bmatrix} \sin(\omega\Delta t) & \cos(\omega\Delta t) \\ \sin(2\omega\Delta t) & \cos(2\omega\Delta t) \\ \vdots & \vdots \\ \sin(N\,\omega\Delta t) & \cos(N\,\omega\Delta t) \\ & \end{bmatrix} \times \begin{bmatrix} V_R \\ V_I \end{bmatrix} = \begin{bmatrix} v(t) \\ v(t-\Delta t) \\ \vdots \\ v(t-(N-1)\Delta t) \end{bmatrix} \qquad (4)$$

$$[A] \times [x] = [B] \qquad (5)$$

$$[x] = [A]^{LPI} \times [B] \qquad (6)$$

$$[A]^{LPI} = \left[[A]^T \times [A]\right]^{-1} \times [A]^T \qquad (7)$$

If a window of 50 samples and frequency of 10 KHz were used, LES filter could estimate phasor parameters in 5 ms. Before the voltage sag, the magnitude and phase angle of *v* could be obtained, respectively

$$V = \sqrt{(V_R^{\,2} + V_I^{\,2})} \qquad (8)$$

$$\theta = \arctan(\frac{V_I}{V_R}) - \omega t\ . \qquad (9)$$

The value of V_{pre} equals numerical value of phase effective voltage, and the value of u_{pre} is identified, using phase freezer unit. When the voltage reduces to less than 0.95 pu., voltage sag detection unit starts phase freezer unit. PLL is not required in this situation due to the fact that voltage angle is estimated by LES filters and is fixed by phase freezer unit. Afterward, a multi-loop control

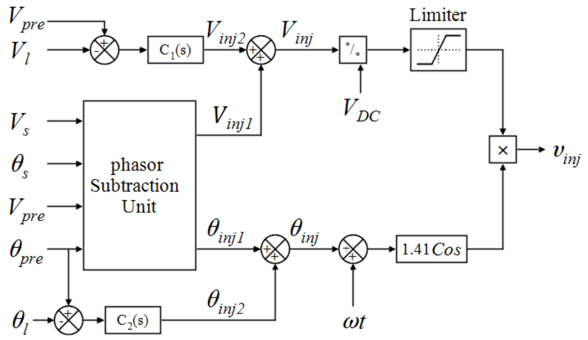

Fig. 3. Phasor-based load voltage control system

The system is used to improve the DVR transient and steady-state responses. This control system includes load voltage control system and an injected voltage control system by Posicast controller. The first system generates a signal to the second.

2.1. Load Voltage Control System

A phasor-based load voltage-control system includes a feed-forward loop for fast response and a feedback loop for zero sequences steady-state error as shown in Fig. 3. Each control loop includes a magnitude control loop and phase control loop which are independent of each other.

According to presag compensation method [28], the injected voltage by the DVR is phasor difference of supply voltage and supply voltage before the voltage sag, and is calculated by phasor subtraction unit based on Fig. 4.

When $V_{pre}\cos\theta_{pre} > V_s\cos\theta_s$, the coefficient γ in (10) is 1 otherwise, it is -1

$$V_{inj1} = \gamma \times \sqrt{\begin{array}{l}\left(V_{pre}\cos\theta_{pre} - V_s\cos\theta_s\right)^2\\ +\left(V_{pre}\sin\theta_{pre} - V_s\sin\theta_s\right)^2\end{array}} \qquad (10)$$

$$\theta_{inj1} = \tan^{-1}\left(\frac{V_{pre}\sin\theta_{pre} - V_s\sin\theta_s}{V_{pre}\cos\theta_{pre} - V_s\cos\theta_s}\right). \qquad (11)$$

Two PI controller (C_1 and C_2) are used to eliminate the steady state error of magnitude and phase of load voltage.

The output of PI controller is added to the output of feed-forward loop. To calculate output phasor of load voltage control loop, the following equation is used

$$v_{inj} = V_{inj}\angle\theta_{inj} = \left(V_{inj1} + V_{inj2}\right)\angle\left(\theta_{inj1} + \theta_{inj2}\right). \qquad (12)$$

To eliminate the effects of DC link voltage on injected voltage, V_{inj} is normalized by V_{DC}. Then, the magnitude is limited by a limiter and acquired magnitude and phase

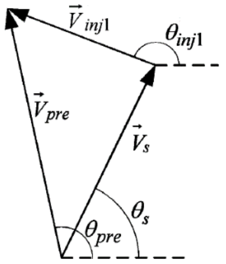

Fig. 4. Vector diagram of the phasor subtraction unit

The angle of injected voltage is turned into a sinusoidal signal.

2.2. Injected Voltage Control System

In this part, to eliminate steady-state error and improve transient response and damping the oscillations at the beginning of voltage sag, a control system includes a P+Resonant and Posicast controller is used according to Fig. 5.

The produced reference signal for injected voltage v_{inj} of is compared with a difference of load and supply measured voltage.

A simple method for compensation voltage sag, injection the produced reference signal v_{inj} to the inverter by sinusoidal pulse width modulation (SPWM) unit. But, the harmonic filter is not capable of eliminating the transient oscillations appropriately in the instant starting of voltage sag.

As it is depicted in Fig. 5, to eliminate the steady-state voltage error, a P+Resonant compensator is added to the voltage control loop. The practical P+Resonant compensator can be mathematically expressed as

$$G_R(s) = k_p + \left(\frac{2k_I\omega_{cut}S}{S^2 + 2\omega_{cut}S + \omega_0^2}\right) \qquad (13)$$

Where k_p and k_I are gain constants and $\omega_0 = 2\pi \times 50$ rad/s is the controller resonant frequency and ω_{cut} is the compensator cutoff frequency, which in this case, is 1 rad/s. The resonant controller eliminates steady-state voltage error by an infinite gain at the resonant frequency of 50 Hz.

The P+Resonant controller response frequency is shown in Fig. 6 shows the resonant peak has a finite gain (40 dB) which is satisfactorily high for eliminating the steady-state voltage error. As shown in Fig. 5, the output of the P+Resonant controller is the reference signal for the filter capacitor current control loop.

It is compared with the measured capacitor current and the error is fed to P controller (C_3). Then output of the the C_3 added with the is added to the feed-forward voltage to generate a signal for Posicast controller.

Posicast controller can be used just before transferring the signal to the inverter. The controller transmission function can be calculated as follow

$$1+G(s)=1+\frac{\delta}{1+\delta}+\left(e^{-s\frac{T_d}{2}}-1\right) \qquad (14)$$

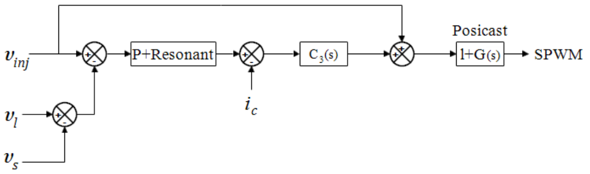

Fig. 5. Instantaneous voltage control system.

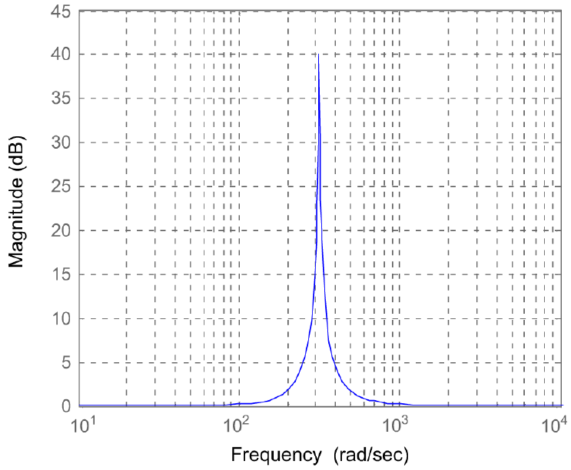

Fig. 6. The magnitude of the P+Resonant controller frequency response

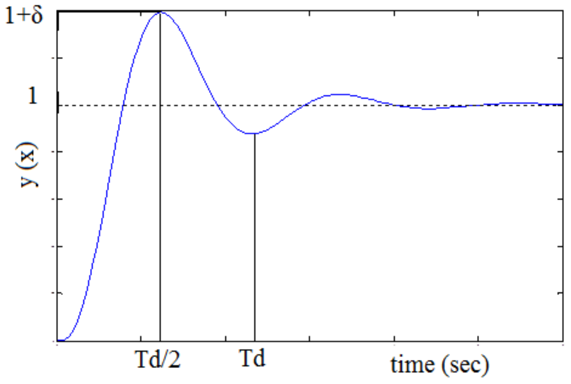

Fig. 7. Step response of the Posicast controller.

The step response of this function (14) shown in Fig. 7.

According to this figure δ and T_d are step response oscillations and damping period of a response signal, respectively. It should be mentioned that Posicast controller has limited high-frequency gain and, thus its sensitivity to noise is low. Therefore, according to definitions of damping and delay, δ and T_d are calculated as follow

$$T_d=\frac{2\pi}{\omega_r}=\frac{\pi}{\sqrt{\frac{1}{L_fC_f}-\frac{R_f^2}{4L_f^2}}} \qquad (15)$$

$$\delta=e^{\xi\pi/\sqrt{1-\xi^2}}=e^{-R_f\pi\sqrt{C_f}/\sqrt{4L_f-R_f^2C_f}}. \qquad (16)$$

3. SIMULATION AND RESULTS

The under study system is IEEE 13-bus balanced industrial system. Single line diagram of this power system is presented in Fig. 8. The efficiency of proposed method is analyzed connecting a big load as distortion source in PSCAD/EMTDC software. Parameters of the control system and load are presented in the Appendix.

The power system is supplied with a 69 kV source and a 13.8 kV generator. The DVR system is located between PCC voltages (bus 03: MILL-1 voltage) and load voltage (bus 05:FDRF voltage) in order to compensate voltage sag. A large induction motor is connected to PCC bus. Characteristics of this load are presented in Appendix. Simulation results are presented in figures 9 to figure 14.

As shown in Fig. 9, load starting current (about 4 kA) makes the voltage of PCC drop in PCC bus. The load is connected to the system at t=0.3 s. Fig. 10 and Fig. 11 depict the effect of using DVR which effectively compensates voltage sag on load bus. In Fig. 12, the instant start of compensation by the DVR , is shown. Fig. 13 shows the speed motor reaches the nominal value in about 0.6 s. As presented in Fig. 14, rms voltage drop of PCC bus is reduced to 0.8 pu. and depicts the load bus voltage by using DVR, effectively returns to the occurrence of voltage sag to the prior situation.

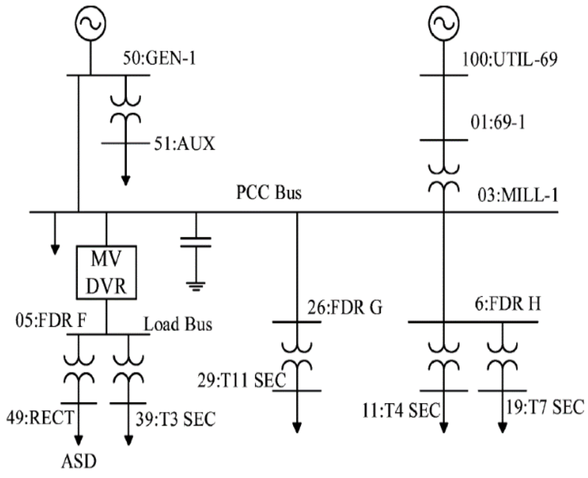

Fig. 8. IEEE standard 13-bus balanced industrial system as understudy test system

Simulation results prove that the proposed control system can operate appropriately under the situation of connection of big load.

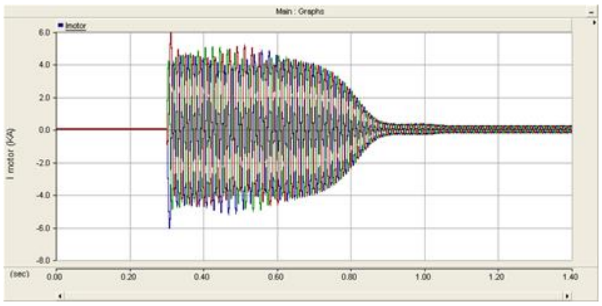

Fig. 9. Starting current of the induction motor

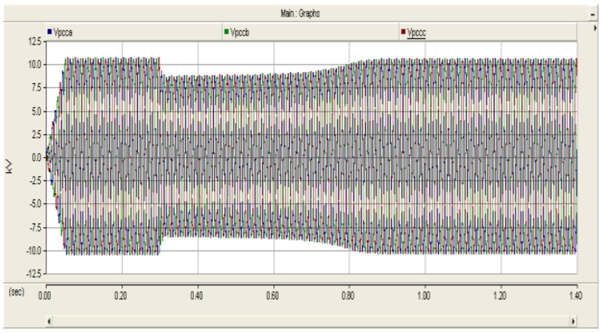

Fig. 10. Three-phase PCC voltages during starting the induction motor

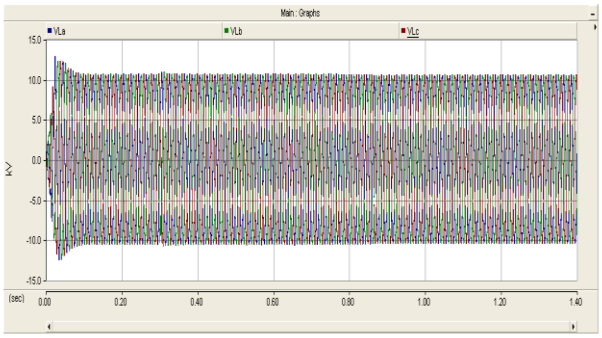

Fig. 11. Three-phase load bus voltages with using the DVR.

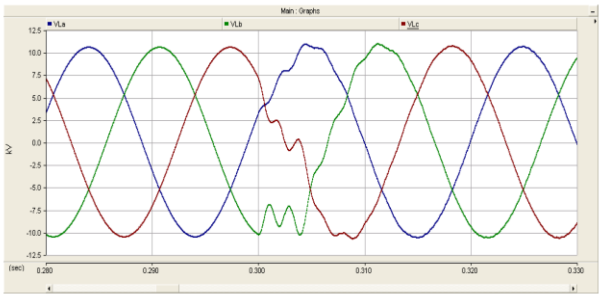

Fig. 12. Start instant of compensation by the DVR.

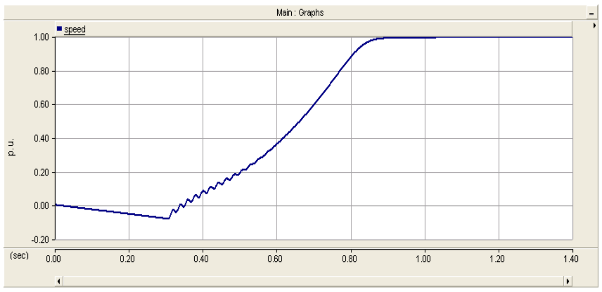

Fig. 13. Induction motor speed.

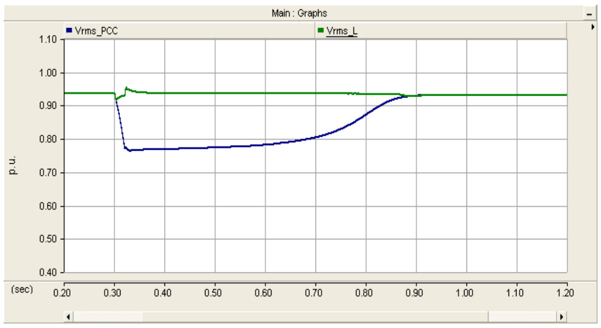

Fig. 14. RMS voltages of PCC and load.

4. CONCLUSION

In this paper, a new control strategy for DVR is proposed. DVR control system is a multi-loop control system, including a load voltage control system and an injected voltage control system by P+Resonant and Posicast controller. Simulation results for the voltage sags under the large induction motor starting in PSCAD/EMTDC software proves that

- the proposed multi-loop control strategy quickly and effectively detects and compensates voltage sag;
- the proposed DVR control system provides desirable transient and steady-state performances under connection of big load.

5. APPENDIX

Table 1. DVR parameters

Parameters	**Value**
Filter inductance (L_f)	0.5 mH
Filter capacitance (C_f)	800 µF
Filter resistance (R_f)	0.12 Ω
DC-link capacitance	56 mF
DC-link rated voltage	746 v
Switching frequency	4.5 KHz
Injection transformer winding ratio	1:1

Table 2. Control system parameters

Controller	k_P	k_I
$C_1(s)$	0.1	80
$C_2(s)$	0.1	600
$C_3(s)$	0.22	0
P+Resonant	1	100
Parameters	**Value**	
δ	1	
T_d	32 μS	
ω_0	314 rad/s	
ω_{cut}	1 rad/s	

Table 3. Induction motor parameters

Parameters	Value
Rated power	2.5 MVA
Rated voltage	13.8 Kv
network frequency	50 Hz
Stator resistance	0.002 p.u.
Rotor resistance	0.36 p.u
Stator inductance	0.01 p.u.
Rotor inductance	0.05 p.u
Magnetizing inductance	0.9 p.u

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