Compensate Voltage Sags in Series Transformers of Dynamic Voltage Restorers for Preventing Saturation

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Abstract

This paper proposes a procedure for preventing saturation in series transformers from Dynamic Voltage Restorer (DVR) systems. Power quality has been an issue that is becoming increasingly pivotal in modern industrial and commercial applications. Voltage disturbances especially the voltage sag and swell are the most common power quality problems due to increased use of a large numbers of sophisticated and sensitive electronic equipment in industrial systems. The method consists in correcting the voltage which is injected through the transformers into the power system to compensate voltage sags. To overcome this problem, custom power devices are used. One of the devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. It is a series connected power electronic based device that can quickly mitigate the voltage sags in the system and restore the load voltage to the pre-fault value. Moreover, the technique allows a certain level of sag compensation even when the estimated flux is expected to exceed the saturation limit. The voltage sag level and phase are computed through an adaptive Recursive Least Squares (RLS). In RLS Method we have to use 4-leg voltage source inverter and it can be slow process to compensate the voltage sag occur in the power system. In extension method, the Adaptive Network based Fuzzy Inference System (ANFIS) is used to reduces the voltage sag in the power system network. In these method, the 3-leg voltage source inverter as comparing to the RLS algorithm. The ANFIS system is faster and accurate to compensate voltage sags in power system. Total harmonics distortions is half of the deduced in the system.

Keywords: Adaptive System Based Fuzzy Interface System (ANFIS), Dynamic Voltage Restorer (DVR), Recursive Least Squares (RLS), Saturation, Series Transformers, Voltage Sag

1. Introduction

Voltage sags are the most episode aggravations perpetrating the power system. Reviews showed that 92% of interferences in electrical equipments may happen because of voltage sags1. The financial effect to the commercial enterprises and utilities is extreme because of hardware harm and loss of creation. To alleviate this issue, the utilities can put supply into the power system plan so as to decrease the flaws rate and the time for their clearance2.

A DVR is a standout amongst the best custom force gadgets for voltage list and swell remuneration and it has been pulling in developing consideration lately. A common test framework, joining a DVR, is portrayed in Figure 1. The DVR infuses repaying voltages to the electrical, cables through a three-stage arrangement transformer or three single-stage arrangement transformers3.

This DVR extends the thoughts grew by managing the likelihood of more prohibitive breaking points for the immersion in the transformer’s center. In the proposed

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2. Method for Controlling Saturation

The key thought is to oblige the remunerating voltage by reproducing it by a structure element. With a specific end goal to perform such an objective, one must anticipate, right now of the hang identification, the worth for the structure variable to be connected up to the end of the following half cycle (or the following entire cycle) of the repaying voltage after the list recognition and keep the flux at its farthest point esteem\(^4\). When all is said in done, \(V_c\) can be portrayed as,

\[
v_c(t) = V \cos(\omega t + \alpha)
\]

Where, \(\omega\) and \(\alpha\) are separately, the fundamental frequency and the beginning period of the compensating voltage. By Faraday’s law, the connected flux in the transformer’s core at a given instant \(t\) can be communicated by,

\[
\lambda = \int_0^t V \cos(\omega T + \alpha)\,dT
\]

Unraveling (2) and expecting that the transformer is demagnetized, that is \(\lambda = 0\) at the \(t = 0\), the accompanying expression for the flux is acquired:

\[
\lambda = (V | \omega|) [\sin(\omega t + \alpha) - \sin(\alpha)]
\]

The first part of (3) represents the ac component of the flux, while the second one is its dc segment. At whatever point the infused voltage began at a zero cross, that is, the crest of the flux achieves its most extreme quality. Case in point, if the expression for the flux is given by,

\[
\lambda = (V | \omega|) [\cos(\omega t) + 1]
\]

The procedure proposed in this paper is motivated by the one portrayed. Consider Figure 2, where the infused voltage begins at point. It is conceivable to anticipate the greatest trip for the flux linkage through the accompanying reconciliation.

\[
\lambda^* = \int_{\pi/2}^{(\pi/2)/\omega} V \cos(\omega t)\,dt + \xi \int_{(\pi/2)/\omega}^{\pi/2} V \cos(\omega t)\,dt
\]

Where \(x\) is a structure component which is initially situated to solidarity. Note that in the middle of \(\alpha\) and \(n/2\), the infused voltage contributes emphatically to the flux. Between \(n/2\) and \(3n/2\), the voltage contributes adversely to the flux. Along these lines, in the circumstance portrayed in Figure 2, at the angle, the flux achieves its base worth.

\[
\xi = -\lambda \max - V \int_{\pi/2}^{(\pi/2)/\omega} \cos(\omega t)\,dt
\]

Applying the component, processed through equation (6), to the compensating voltage amid its negative semi cycle, guarantees that the flux won’t surpass as far as possible. At the point when the infused voltage begins inside of a negative semi cycle, at the point, is predicted through

\[
\lambda^* = \int_{\pi/2}^{(\pi/2)/\omega} V \cos(\omega t)\,dt + \xi \int_{(\pi/2)/\omega}^{\pi/2} V \cos(\omega t)\,dt
\]

On the off chance that, the infused voltage is obliged to be scaled by the structure variable figured by

\[
\xi = -\lambda \max - V \int_{\pi/2}^{(\pi/2)/\omega} \cos(\omega t)\,dt
\]

It must be noticed that the methodology portrayed before just moves the flux bend so that, up to end of the semi cycle, along these lines after the begin of the voltage infusion, its esteem is not higher than the transformer’s flux limit. Despite everything it remains a dc part which can bring about the flux quality to surpass as far
as possible inside of the consequent inverse semi cycle. In this manner, in the proposed technique, the condition
\[ |\lambda_{\text{max}}| \leq |V/\omega| \] (9)
must be confirmed. Note that V is the top worth for the repaying voltage. In the event that the condition (9) is not watched, the repaying voltage must be figured as
\[ v_s(t) = \frac{V_{\text{max}}}{2} \cos(\omega t + \alpha), \]
for \[ \alpha \leq \omega t \leq \alpha + \frac{\pi}{2} \] (10)

Where \( V_{\text{max}} = \lambda_{\text{max}} \omega \).

In this proposed method, needed to compute the amplitude and phase of the compensate voltage is carried out by RLS. More over for each instant updates the amplitude and phase estimation. During estimation transients occur there is no compensating voltage injected into the grid as discussed in Figure 3.

3. Compensating Voltage Construction

The compensating voltage development connected in this paper makes utilization of a RLS algorithm which processes the amplitude and the phase for every specimen of the grid voltage. The accompanying one layout the strategy in which the compensating voltage is just infused when the RLS estimation is consistent.

3.1 RLS Estimator

RLS estimator is regular to portray them as a whole of sinusoids, with one being the basic, and the others are being harmonics. On the off chance that the voltage is undermined by harmonics, this representation guarantees that the flow of the harmonics don’t debase the parameters estimation identified with the major sinusoid. Consequently, indicate the information of voltages by \( V_g \), the model is an entirety of p sinusoids gave by,
\[ v_s(n) = \sum_{m=1}^{P} V_{Gm} \cos(m \omega_0 n + \alpha_m) \]

Where \( V_{Gm} \) and \( \alpha_m \) are, separately, the amplitude and the phase of the sinusoid of \( m \omega_0 \) frequency, and \( n \) is the time file. The time interm is the \( \Delta t \) inspecting period. Its choice does not meddle with the RLS execution once the Nyquist criterion is observed. The principal of \( P \) the sinusoids is identified with the essential phasor. The model portrayed by (11) is not pertinent for the RLS calculation. The parameters \( \alpha_m \) are not straight concerning the model \( \hat{v}_g \). Along these lines, the model is revised as
\[ \hat{v}_g[n] = \sum_{m=1}^{P} [V_{Gm} \cos(m \omega_0 n \Delta t + \alpha'_m) \sin(m \omega_0 n \Delta t)] \]

Where \( V_{Gm} \) and \( \alpha_m \) are, identified with the model (11) through mathematical statements
\[ V_{Gm} = \sqrt{V_{Gm}^2 + V_{Gm}^2} \] (13)

\[ \alpha_m = -\arctan(V_{Gm} / V_{Gm}) \] (14)
Mathematical statement (12) can minimum be composed as

\[
\hat{v}_x[n] = \phi^T_n \varphi_n 
\]  

(15)

Where \( \varphi_n \) is a vector of regressors given by

\[
\varphi_n = \begin{bmatrix}
\cos(\alpha_n t) \\
\sin(\alpha_n t) \\
\cos(p\alpha_n t) \\
\sin(p\alpha_n t)
\end{bmatrix}
\]  

(16)

What's more \( \varphi_n \) is a vector of parameters to be resolved and whose components are given by

\[
\varphi_n = [V_{G1}^c - V_{G1}, \ldots, V_{Gp}^c - V_{Gp}]^T
\]  

(17)

It should be noticed that the subscript \( n \) in \( \varphi_n \) alludes to the estimation of the parameters did for the moment \( n\Delta t \). For example, the component \( \varphi_{n1} \) is the estimation of \( V_{G1}^c \) for the moment \( n\Delta t \). The dissonance between the information signal \( v_x \) and its model \( \hat{v}_x \) at a given moment \( t_n \) is the expectation lapse \( e[n] \), gave by

\[
\hat{\phi}_{n+1} = \hat{\phi}_n + K_{n+1} e[n+1]
\]  

(18)

The RLS calculation upgrade the estimation for the parameter as indicated by the accompanying mathematical statement:

\[
\hat{\phi}_{n+1} = \hat{\phi}_n + K_{n+1} e[n+1]
\]  

(19)

Where \( K_{n+1} \) is an increase given by

\[
K_n = P_n \varphi_n
\]  

(20)

Further more \( P_n \) is the proposed covariance framework which is redesigned by the accompanying recursive mathematical statement:

\[
P_{n+1} = P_n - \frac{P_n \varphi_n \varphi_n^T P_n}{1 + \varphi_n^T P_n \varphi_n}
\]  

(21)

In this system, the covariance lattice is upgraded by taking after guideline:

\[
P_{n+1} = \begin{cases}
P_n - \frac{P_n \varphi_n \varphi_n^T P_n}{1 + \varphi_n^T P_n \varphi_n}, & \text{if } |e[n]| \leq \varepsilon, \\
P_n + R & \text{if } |e[n]| > \varepsilon
\end{cases}
\]  

(22)

Where \( \varepsilon \) and \( R \) are subjectively balanced. This present calculation's structure is suitable for the proposed flux control application.8

3.2 Constant Level Detection

Keeping in mind the end goal to identify a steady level for the parameters estimation, one can normal a length moving window for the estimation of the amplitude \( V_{G1} \) through the mathematical statement.

\[
M[n] = \frac{1}{N} \sum_{j=n-N+1}^{n} V_g[j]
\]  

(23)

Where \( n \) is the last example of the amplitude estimation.9 This normal can be utilized to compute a sum \( S \) given by,

\[
S = \sum_{j=n-N+1}^{n} |M[j] - V_{G1}/|J|
\]  

(24)

The compensating voltage \( v_s \) is injected by the DVR as

\[
v_s(n\Delta t) = \begin{cases}
V \cos(\omega n\Delta t + \alpha_i), & \text{if } flag = 1 \\
0, & \text{if } flag = 0
\end{cases}
\]  

(25)

Where \( V \) is the difference between a reference value \( V_{ref} \) and the estimated \( V_{Gm} \).

4. Simulation Results

The performance of the proposed algorithm, a DVR system has been simulated by using the simulink power system and simulink from Matlab. In Figure 4, it can be observed the compensating voltage is injected by four-leg Voltage Source Inverter (VSI) controlled by a pulse-width modulation (PWM).

The three different cases voltage sags are occur, in the first case consider that a three phase grid is under a phase to phase sag during 0.5ms in Figure 5(a). In Figure 5(b) shows the least square amplitude for phase-A raises from 0 to 360v and it still constant up to 0.5ms and then decreases to 300v up to the 1ms.In Figure 5(c) shows the

![Figure 4. Simulation platform of the DVR system.](image-url)
injected voltage by the DVR for the phase A, is ignited 10v at the exact voltage sag is occur. In Figure 5(d) shows the corrected load voltages.

In second case, the voltage sag is obtained in Figure 6(a) it shows the phase to phase fault is present at 0.5m, for an angle $\alpha$ is different for previous one. Figure 6(b) shows the amplitude carried out by the least square algorithm for phase A is raises from 0 to 360v and will be constant amplitude up to 0.5ms and decreases from 360v to 260v. In Figure 6(c) shows the voltages injected by the DVR into the grid. The compensating voltages would be injected without any control for the saturation. In Figure 6(d) shows the voltages applied to the load.

In third case, simulates the sag for single phase, as represented in Figure 7(a). It is similar to the other cases. In Figure 7(b) shows the RLS amplitude for the sagged voltage from 0v to 360v up to the 0.5ms and then the amplitude is decreased to half of the amplitude 160v. In Figure 7(c) shows the voltage without any constraint with the control of saturation. Figure 7(d) shows the applied voltages to the load.

5. Extension Work

The extension of the given proposed system can be done by adding an Adaptive Network based Fuzzy Inference System in The place of adaptive Recursive Least Squares (RLS) as shown in Figure 8.

6. Adaptive Network Based Fuzzy Inference System

This section introduces the basics of ANFIS network architecture and its hybrid learning rule. Inspired by the
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Case 3

![Simulated results for the DVR system: Case 3.](image1)

(a) Voltage sags on phase A.
(b) Amplitude estimation of phase A.
(c) Compensating voltages injected by the DVR.
(d) Corrected voltages applied to the load

![Simulation platform of the ANFIS system.](image2)

Figure 9. Adaptive Neuro-Fuzzy Inference System.

Inference System, whose architecture is shown in Figure 9. He reported that the ANFIS architecture can be employed to model nonlinear functions, identify nonlinear components on-line in a control system, and predict a chaotic time series. It is a hybrid neuro-fuzzy technique that brings learning capabilities of neural networks to fuzzy inference systems. The learning algorithm tunes the membership functions of a Sugeno-type Fuzzy Inference System using the training input-output data. The ANFIS is, from the topology point of view, an implementation of a representative fuzzy inference system using a Back Propagation (BP) neural network-like structure. It consists of five layers.

In Figure 9 ANFIS the parameters can be assessed in such a course, to the point that both the Sugeno and Tsukamoto cushioned models are identified with by the ANFIS structural engineering. Again with minor objectives the ANFIS model takes after the Radial Basis Function Network (RBFN) essentially. This ANFIS system contains a blend course of action of fuzzy rationale and neural system procedure. The fuzzy rationale considers the imprecision and trembling of the structure that is being shown while the neural system gives it an inclination of flexibility.

The performance of the ANFIS system has been simulated by using the simulink power system and simulink from matlab. In Figure 4, it can be observed the compensating voltage is injected by three-leg Voltage Source Inverter (VSI) controlled by a Pulse-Width Modulation (PWM).

The three different cases voltage sags are occur, in the first case consider that a three phase grid is under a phase to phase sag during 0.5ms in Figure 10(a). In Figure
(b) Amplitude estimation of phase A.
(c) Compensating voltages injected by the ANFIS.
(d) Corrected voltages applied to the load.

Figure 10. Simulated results for the ANFIS system: Case 1.
(a) Voltage sags on phase A.
(b) Amplitude estimation of phase A.
(c) Compensating voltages injected by the ANFIS.
(d) Corrected voltages applied to the load.

10(b) shows the least square amplitude for phase-A raises from 0 to 360v and it still constant up to 0.5ms and then decreases to 300v up to the 1ms.In Figure 10(c) shows the injected voltage by the ANFIS for the phase A, is ignited 10v at the exact voltage sag is occur. In Figure 10(d) shows the corrected load voltages.

In second case, the voltage sag is obtained in Figure 11(a) it shows the phase to phase fault is present at 0.5m, for an angle \( \alpha \) is different for previous one. Figure 11(b) shows the amplitude carried out by the least square algorithm for phase A is raises from 0 to 360v and will be constant amplitude up to 0.5ms and decreases from 360v to 260v. In Figure 11(c) shows the voltages injected by the ANFIS into the grid. The compensating voltages would be injected without any control for the saturation. In Figure 11(d) shows the voltages applied to the load.

In third case, simulates the sag for single phase, as represented in Figure 12(a). It is similar to the other cases. In Figure 12(b) shows the RLS amplitude for the sagged voltage from 0v to 360v up to the 0.5ms and then the amplitude is decreased to half of the amplitude 160v.In Figure 12(c) shows the voltage without any constraint with the control of saturation. Figure 12(d) shows the applied voltages to the load.

In extension method, the ANFIS is used power sag amplitude is reduce 50% of actual voltage and raises to unity. The ANFIS is very faster and cheaper. In these method, 3-VSI is used and total harmonics distortion is reduces. ANFIS is a hybrid intelligent system which implements a Surgeon fuzzy inference system for a systematic approach to generating fuzzy rules from a given input output dataset. These techniques provide a method for the fuzzy modeling procedure to learn information about data set, in order to compute the membership function parameters that best allow the associated fuzzy inference system to track the given input-output data.

By comparing the THD values of the DVR system is 0.10% and in ANFIS system THD value is 0.05% in Figure 13.
7. Conclusion

This paper has proposed a technique for controlling flux immersion in transformers utilized by a DVR system. The DVR system makes utilization of a RLS calculation to process the compensating voltage. The strategy depends on the right processing of the compensating voltage phasor which is compelled at whatever point it can incite immersion. The compensation is never rendered while the RLS amplitude phasor estimation is varying. DVRs are effective custom power devices for voltage sags and swells mitigation; they inject the appropriate voltage component to correct rapidly any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value. In the present paper a reliable controller with high performance for dynamic voltage restorers was proposed. The proposed controller is generated by ANFIS training according to a given input output data. Compared to the traditional fuzzy controller, the proposed one is the simplest and the most cost effective. In addition this controller has no gains to adjust and solve the problem of traditional fuzzy controller gains tuning.

8. References

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Figure 12. Simulated results for the ANFIS system:
Case 3.
(a) Voltage sags on phase A.
(b) Amplitude estimation of phase A.
(c) Compensating voltages injected by the ANFIS.
(d) Corrected voltages applied to the load.

Figure 13. THD comparison.
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