Balanced Voltage Sag Correction Using Dynamic Voltage Restorer Based Fuzzy Polar Controller

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Abstract

This project proposes a technique for preventing saturation in series transformers from dynamic voltage restorer (DVR) systems. The method consists in correcting the voltages which are injected through the transformers into the power system to compensate voltage sags. It restricts the compensating voltages during the sag whenever it predicts that a maximum limit for the flux linkage is about to be exceeded. The prediction is carried out at the beginning of stabilized voltage sag. 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). The RLS estimation incorporates a transient period before it achieves a stable state whenever there is a sag event. The DVR is not supposed to operate in this period. Therefore, this paper also outlines a simple procedure for detecting the RLS estimation stable level. Simulation of different scenarios of voltage sags and the results from the experimental implementation of a DVR show the effectiveness of the method. Fuzzy gains usually perform fine in the original system. This total project done in MATLAB SIMULATION Software.

Key words: Dynamic voltage restorer (DVR), flux linkage, power quality (PQ), recursive least squares, saturation, transformer.

1. Introduction

Voltage sags are the most incident disturbances in- flicting the power system. Surveys indicated that 92% of interruptions in industrial facilities may occur due to voltage sags. The economic impact to the industries and utilities is severe due to equipment damage and loss of production. To mitigate this problem, the utilities can invest in the power system design in order to reduce the faults incidence and the time for their clearance. Also, redundant lines can be installed to feed critical loads. Unfortunately, these solutions are complex and costly to implement. This enables local-based alternatives where some equipment is fixed in the system-load interface. One example of this approach is the usage of dynamic voltage restorers (DVRs). A DVR is one of the most effective custom power devices for voltage sag and swell compensation and it has been attracting growing attention in recent years. A typical test system, incorporating a DVR, is depicted in Fig. 1. The DVR injects compensating voltages to the power lines through a three-phase series transformer or three single-phase series transformers. A problem may arise when the DVR system corrects a severe sag. In this situation, the compensating voltages can cause flux linkage in the core to exceed the transformer nominal limit. The exceeding flux is caused by a dc component whose amplitude depends on the initial phase angle of the compensating voltage. This, in turn, leads to overcurrent and overheating, reducing the useful life of the transformer. To overcome this problem, one alternative is to enlarge the series transformers. This solution brings an increase in physical size, weight, and cost to the transformer. Another approach is to apply DVR systems without transformers. This increases the number of switches and their associated control circuits needed to apply the compensating voltage. Finally, there is the strategy of controlling the flux linkage by limiting the voltage injected to compensate the sag. This approach has a compromising nature. It deals with the necessity of reducing the sag and the demand of not changing the transformer’s flux limit. The flux linkage in the DVR’s transformers is kept under a maximum limit by shutting off the reference voltages while the currents are over a specified limit, or the reference voltages are reversed. The drawback is to impose a full sag to the load during a certain period. In the controller uses the mag- nitude
of the positive-sequence component of the line voltages to identify voltage sags. The flux is estimated by means of the integral of the voltage and whenever it reaches a given limit, the voltage is set to zero. The method proposed in also makes use of the flux estimation in order to limit the compensating voltages. The voltage injection action is divided into three intervals. Between the sag detection instant and one-sixth of the fundamental period, after the sag detection, the injected compensating voltage is fully applied to compensate the sag. Between The inrush control systems for all of the aforementioned works rely on the estimation of the load voltage phasors to compute the compensating voltages. Some works employ the standard least-squares error to estimate these phasors, notwithstanding, in general, that the techniques for estimating them are not exploited or discussed by the authors. This paper expands the ideas developed in by dealing with the possibility of more restrictive limits for the saturation in the transformer’s core. In addition, it proposes the use of an adaptive RLS-based technique for the estimation of phasors, suitable to be incorporated to the compensation voltage control as well as the inrush control. The voltage phasor amplitudes are employed to verify whether the flux surpasses the transformer’s flux limit. The RLS algorithm necessarily includes a transition time before its estimation achieves a constant level. In the proposed method, it is assumed that the DVR system should not operate before it has a stabilized reference for the sag. Therefore, this paper also proposes a simple procedure to detect whether the RLS estimation reaches a constant value for the

2. Method For Controlling Saturation

This section devises the method of controlling saturation proposed in this paper. The fundamental idea is to constrain the compensating voltage by multiplying it by a form factor. In order to accomplish such a goal, one must predict, at the moment of the sag detection, the value for the form factor to be applied up to the end of the next half cycle (or the next whole cycle) of the compensating voltage after the sag detection and keep the flux at its limit value. In general, can be described as

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

\[ \lambda = \int_0^t V \cos(\omega \tau + \alpha) d\tau. \]

Solving and assuming that the transformer is demagnetized, the following expression for the flux is obtained:

\[ \lambda = \left(\frac{V}{\omega}\right)[\sin(\omega t + \alpha) - \sin(\alpha)].\]
The first part of the flux represents the ac component of the flux, while the second one is its dc component. Whenever the injected voltage started at a zero cross, that is, the peak of the flux reaches its maximum value. For instance, if the expression for the flux is given by:

\[ \lambda = \int_{0}^{\pi/2} V \cos(\omega t) dt + \xi \int_{\pi/2}^{3\pi/2} V \cos(\omega t) dt \]  

where \( \xi \) is a form factor which is first set to unity. Note that between 0 and \( \pi/2 \), the injected voltage contributes positively to the flux. Between \( \pi/2 \) and \( 3\pi/2 \), the voltage contributes negatively to the flux.

\[ \xi = \frac{-\lambda_{max} - V \int_{0}^{\pi/2} \cos(\omega t) dt}{\int_{0}^{3\pi/2} V \cos(\omega t) dt} \]  

Applying the factor \( \xi \), computed through (6), to the compensating voltage during its negative semicycle, ensures that the flux will not surpass the minimum limit. When the injected voltage starts within a negative semicycle, the predicted flux is computed as

\[ n_{c}(t) = \frac{V_{max}}{2} \cos(\omega t + \alpha), \text{ for } \alpha \leq \omega t \leq \alpha + \pi/2 \]  

Fig. 2. Compensating voltage for one of the phases. 

must be verified. Note that is the peak value for the compensating voltage. If the condition is not observed, the compensating voltage must be computed as

3. Compensating Voltage Construction

The compensating voltage construction applied in this paper makes use of an RLS algorithm which computes the amplitude and the phase for each sample of the grid voltage. The RLS algorithm is applied for each one of the three grid phases. It is worth emphasizing that the DVR is not meant to compensate the voltage while the RLS estimation is in its transient period. Therefore, in this paper, a method is proposed for flagging whether the RLS estimation is stable. The next subsection is dedicated to explain the RLS algorithm used in this paper. The following one outlines the procedure in which the compensating voltage is only injected when the RLS estimation is constant.

3.1 RLS Estimator:

To model voltages acquired from power systems, it is usual to describe them as a sum of sinusoids, with one being the fundamental, and the
others being harmonics. If the voltage is corrupted by harmonics, this representation ensures that the dynamics of the harmonics do not contaminate the parameters estimation related to the fundamental sinusoid. Hence, denoting the data of voltages by $\mathbf{v}$, the model is a sum of sinusoids provided by

$$\hat{v}_g(n \Delta t) = \hat{v}_g[n] = \sum_{m=1}^{p} (V_{Gm} \cos(m \omega_0 n \Delta t + \alpha_m))$$

- (7)

interval is the sampling period. Its selection does not interfere with the RLS performance once the Nyquist criterion is observed. The first of the sinusoids is related to the fundamental phasor. The model described is not applicable for the RLS algorithm. The parameters are not linear with respect to the model. Thus, the model is rewritten as

$$\hat{v}_g[n] = \sum_{m=1}^{p} [V_{Gm}^c \cos(m \omega_0 n \Delta t) - V_{Gm}^s \sin(m \omega_0 n \Delta t)]$$

where and are related to the model through equations

$$V_{Gm} = \sqrt{(V_{Gm}^c)^2 + (V_{Gm}^s)^2}$$

$$\alpha_m = -\arctan \left( \frac{V_{Gm}^s}{V_{Gm}^c} \right).$$

- (9)

$$\phi_n = \begin{bmatrix} \cos(\omega_0 n \Delta t) \\ \sin(\omega_0 n \Delta t) \\ \vdots \\ \cos(p \omega_0 n \Delta t) \\ \sin(p \omega_0 n \Delta t) \end{bmatrix}$$

- (10)

vector of parameters to be determined and whose elements are given by

$$\varphi_n = [V_{G1}^c - V_{G1}^s \cdots V_{Gp}^c - V_{Gp}^s]^T.$$
Before the algorithm is triggered, the initial covariance matrix must be adjusted. Usually, this initial matrix is set to be diagonal with the elements that have high values in comparison with the values of the parameters to be estimated. Then, this matrix has a higher norm in a sense that it has greater capability to modify a norm of a vector which is multiplied by it. During the RLS application, as the estimative converges for the true values of the parameters, the norm is reduced. Hence, this algorithm is not intrinsically adaptive. In order to provide adaptability for the RLS, it must be added to some mechanism where the covariance matrix is updated so that its norm value is always within an adequate range. The technique selected in this paper is designated modified random walking (MRW).

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

where and are arbitrarily adjusted. This algorithm’s structure is suitable for the proposed flux control application. The monitoring of the error can be used not only to provide adaptability for the RLS, but also to detect the voltage sag.

The DVR action must be performed only after the transient of the parameters estimation. Thus, the next subsection outlines a simple manner of detecting when the transient is finished, that is, a mean of detecting the constant level for the parameters estimation.

### 3.2 Constant Level Detection

In order to detect a constant level for the parameters estimation, one can average an -length moving window for the estimation of the amplitude through the equation

\[
M[n] = \frac{1}{N} \sum_{j=n-N+1}^{n} V_{G1}[j]
\]

where is the last sample of the amplitude estimation. This average can be used to compute a sum given by

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

This sum tends to be zero whenever the parameters estimation is a constant level. Hence, if is less or equal to a given limit immediately after a sag detection, one can ensure that the RLS estimation for the parameters, that is, the amplitude and phase of the sag, has passed its transition time. For each voltage sample, the RLS algorithm computes the phase and the amplitude which is provided to the constant level detector. This detector sets a flag signal to 1 whenever the parameters estimation is stable. On the instant that the parameters start changing, the RLS sets the flag signal to 0. Therefore, the flag signal can be used as an enable signal to the DVR action. The compensating voltage is injected.

### 4. Using Fuzzy Logic

Fuzzy Logic has two different meanings. Fuzzy Logic is a logical system, which is an extension of multivalve logic. However, in a more extensive sense Fuzzy Logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp limits in which membership is a matter of degree. Fuzzy logic controllers have the advantages of operating with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity. Fuzzy logic control generally consists of three stages: fuzzification, Inference, and Defuzzification. For simplicity a membership capabilities is Triangular. Fuzzification is using continuous universe of discourse. Implication is using Mamdani’s "min" operator.
Defuzzification is using the "height" method. FLC block diagram.

The nonlinear fuzzy logic controller is used to overcome the problems generated by different uncertainties existing in power systems when designing electromechanical oscillation damping controllers. Power systems are large scale systems with high nonlinearity, so there is a considerable uncertainty in every part of them. Fuzzy logic performs as a powerful tool to confront these uncertainties. Fuzzy Logic is an advantageous approach to diagram input space to a output space. Mapping input to output is the beginning phase for everything. Consider the following examples: With data about how good your service was at a restaurant, a fuzzy logic system can tell you what the tip should be.

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Fig.4: Block diagram of Fuzzy Logic Controller

### 4.1 Fuzzification

Membership capability values are assigned to linguistic variables, using seven fuzzy subsets. NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big).

Fuzzy Inference is a method that interprets the values in the input vector and, based on user defined rules, allots values to the output vector.

Utilizing the GUI editors and viewers in the Fuzzy Logic Toolbox, you can construct the rules set, define the membership capabilities, and analyze the behavior of a Fuzzy Inference System (FIS).

Key features:
- Specialized guis for building fuzzy inference systems and review and analyzing results.
- Membership capabilities for making fuzzy inference systems.
- Support for AND, OR, and NOT logic in user defined rules.
- Standard Mamdani and Sugeno-sort fuzzy inference systems.
- Automated membership capability shaping through neuro adaptive and fuzzy clustering learning methods.
- Ability to insert a fuzzy inference system in a Simulink model.

### 5. Simulation Model and Results

**Case (i): three-phase grid is under a phase-to-phase sag:**
Fig: 5.1 Voltage sags on phases

Fig: 5.2 Amplitude estimation of phase-A

Fig: 5.3 Corrected voltages applied to the load.

Case(ii): voltage sag is depicted

Fig: 5.4 Voltage sags on phases

Fig: 5.5 Amplitude estimation of phase-A

Case (iii): Using Fuzzy logic control

Fig: 5.6 Voltage sags on phases

Fig 5.7: Amplitude estimation of phase-A

CONCLUSION

This project has proposed a technique for controlling flux saturation in transformers utilized by DVR systems. The DVR systems make utilization of a RLS algorithm to register the compensating voltage. The technique depends on the right calculation of the compensating voltage phasor which is obliged at whatever point it can incite saturation. The pay is never rendered while the RLS plentifulness phasor estimation
is fluctuating. Subsequently, the RLS calculation is consolidated with a procedure for recognizing whether the estimation for the amplitude achieved a steady esteem. This guarantees the compensate ding voltage is dependably at a legitimate level.

At times, this is performed at an expense of not totally compensate ding the list for a specific timeframe. However, this is a trade off answer for be connected to burdens which can withstand some level of hang inside a restricted period. The technique has been put on test by reenactments of various situations of voltage sags. Moreover, a DVR model, including the proposed strategy, has been set up. For the contemplated cases, the outcomes demonstrate that the heap voltages are appropriately rectified in under one principal cycle, which is an entirely tasteful time for an extensive class of burdens.

REFERENCES


