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Voltage Sag Compensation with DVR in Power Distribution System Based on Improved Cuckoo Search Tree-Fuzzy Rule Based Classifier Algorithm

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Abstract

A new technique presents to improve the performance of dynamic voltage restorer (DVR) for voltage sag mitigation. This control scheme is based on cuckoo search algorithm with tree fuzzy rule based classifier (CSA-TFRC). CSA is used for optimizing the output of TFRC so the classification output of the network is enhanced. While, the combination of cuckoo search algorithm, fuzzy and decision tree classifier can create a hybrid classifier. Here, Fuzzy and decision tree algorithm will be sufficiently combined with cuckoo search algorithm. The proposed CSA-TFRC algorithm based DVR is simulated in MATLAB software with comparison of traditional DVR and neuro-fuzzy based DVR. Results show the ability of proposed algorithm to detect the voltage sag and make a fast compensation deals.

Keywords: DVR; Voltage sag mitigation; Tree fuzzy rule based classifier; Cuckoo search algorithm.
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1. Introduction

A) *Motivation*

Today, the dip and distortions in voltage and current waveforms have shown much attention because of awareness of power quality (PQ) in distribution loads. In present day, the process control of food, textile and different manufacturing industries are working based on modern computerized equipment are sensitive to supply disturbances and interruptions [1-2]. This increase in sensitive loads makes PQ problems very important in distribution loads [3-4].

DVR is series type compensating device which is used for voltage sag mitigation in distribution network. This device is capable for maintaining load voltage very close to rated value by injecting a series voltage to the source [5]. The voltage sag mitigation in the DVR can be obtained by reactive power injection. This reactive power injection is capable to compensate a minimum amount of voltage drop [6-7]. In these cases, it is essential for transferring active power from dc bus source and the DVR compensating capacity depends upon the maximum inverter voltage and dc bus stored energy [8]. Performance and utilization of DVR depends upon design of control strategy used for derivation of fundamental component of source voltages.

B) *Literature survey*

Many different DVR circuit topologies are available in literature. The different control techniques of DVR have been evaluated based on phase angle jump and voltage sag. The 'in-phase compensation' and 'pre-sag compensation' are two methods have been proposed [9-10].

In order to improve the PQ [11], artificial neural networks (ANNs) and fuzzy logic controller (FLC) are mostly used in addition. Reference [12] has proposed neuro-fuzzy controller (NFC) based DVR, where the DC link capacitor discharging time is reduced by installing a bias voltage generator. In the first stage, the fault voltage and error voltage will be gained. Then, the voltage deviation has been applied separately to FLC and ANN.

The tree-fuzzy rule based classifier (TFRC) is used for improving processing the speed, robustness, response, tracking ability, precision, accuracy, transient and steady-state stabilities etc. [13]. The cuckoo search based techniques have gained much attention in PQ area due to improved response. The CSA algorithm is used to optimize the output of the TFRC. In the optimized interference system, the rules are generated by the optimal value of the regulated voltage.

This paper proposes an improved cuckoo search tree-fuzzy rule based classifier algorithm to a three phase DVR for voltage sag mitigating.

C) *Contribution*

In this paper, CSA based TFRC is suggested for improving the performance of DVR to compensate the voltage sag with a very fast dynamic response. The objective of this work is to develop an algorithm for voltage and error of voltage data classification for voltage sag analysis in a power distribution system. Numerous methods were implemented to voltage sag prediction in a fast way. In order to attaining the capable consequence it is designed to provide rule based voltage data sets maintain system depend on computer aided analysis technique. This method improved to grow information routinely from patterns or unprocessed data. The comprehensive levels implicated voltage decision support systems are in three procedure 1) Data pre-processing, 2) generating decision rules and rule weighting 3) classification. Primarily, the duplicate record, missing data, noisy in the reliable data will be detached from the database in pre-processing. After that, characteristic element dimension technique will be implemented to decrease the features space using orthogonal local preserving projection (OLPP) algorithm. Then, by merging the cuckoo search algorithm, fuzzy and decision tree classifier, we will extend a fusion classifier. Here, Fuzzy and decision tree algorithms will be efficiently mutual with CSA and which will show the way for precise classification to classify normal and voltage sag conditions. CSA-TFRC will be exploited and the performance proposed system will acquire with the costing metrics such as sensitivity, specificity and accuracy. The proposed system will be executed using MATLAB.

D) *Organization of the paper*

The remainder of the paper is organized as follows. Section 2 describes the problem formulation. The proposed control strategy is developed in section 3. Results and discussion to solve the problem is provided in Section 4. Conclusions are presented in Section 5.

2. Problem Formulation

A schematic diagram of DVR is depicted in Fig.1 where AC source is feeding to distribution loads. The main components of DVR are injecting transformer, series (R_f and C_f) filter, VSC and interfacing inductor (L_f). To mitigate high frequency harmonics at injecting transformer, a (R_f and C_f) filter is connected and required compensating voltages ($v_{dvr,a}$, $v_{dvr,b}$, $v_{dvr,c}$) is injected by DVR for voltage sag compensation. In control strategy, source voltages (v_{sa},v_{sb},v_{sc}), source currents, load terminal voltage (v_{Lt}), dc link voltage (v_{dc}) and source terminal voltage (v_{st}) are required to generate fundamental load voltages (v_{La}*, v_{Lb}*, v_{Lc}*,) is depicted in Fig. 1. The distorted source voltages are passed through Band Pass Filters (BPFs) to mitigate harmonics and noise.

The dc link capacitor (C_{dc}) voltage regulation and the voltage injection problems are solved quickly in this proposed algorithm. All these processes have improved the performance of DVR system compared to the conventional system. The block diagram of the proposed CSA-TFRC based DVR system is illustrated in Fig.2.

Fig. 2 shows the structure of the proposed DVR system with the working of the CSA-TFRC exposition. Here, the input voltage, line voltage, output voltage, regulated voltage, and injected voltage are denoted as V_s, V_{line}, V_{load}, V_R and V_{inj} respectively. If the injected voltage satisfies the conditions;

$$\begin{cases} V_{inj} = \sqrt{(V_{load}^2 - V_{sag}^2)} & if:\ V_S < \sqrt{(V_{load}^2 - V_{sag}^2)} \\ V_{inj} = V_S & if:\ V_S > \sqrt{(V_{load}^2 - V_{sag}^2)} \end{cases} \qquad (1)$$

Then the voltage sag of the system is compensated perfectly. The active power of the system depends on the injected voltage of the transformer. So, the minimum injection of active power is achieved by regulating the dc-link voltage of the system. The regulation of voltage of the dc-link capacitor depends on the requirement of the DVR system.

The proposed DVR system is the combination of CSA with tree fuzzy rule based classifier system. The CSA algorithm is used to optimize the output of the TFRC. Then, based on the CSA output, an optimized fuzzy system is developed. In the optimized interference system, the rules are generated based on the optimal value of the regulated voltage.

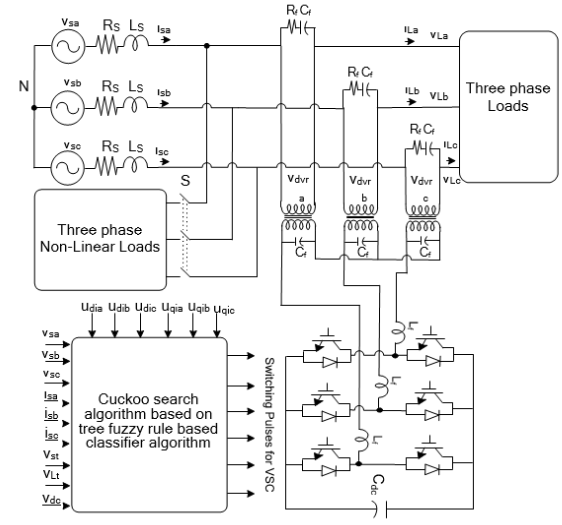


Fig.1 Single line diagram of DVR

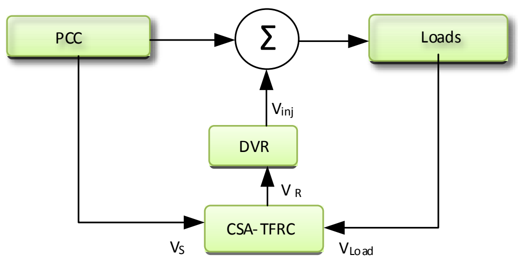


Fig.2 Proposed CSA-TFRC based DVR system

In the existent power distribution data are normally imperfect, noisy, and unpredictable. If imperfect means missing characteristic values, missing definite characteristic of attention, or having only collective of data. Noisy means enclosing faults or outliners. Unpredictable means having inconsistency in codes or names. Mostly we achieve a data cleaning, data integration, data transformation, data reduction, data discretization but in this paper we will reduce a dimension of the missing attributes.

A) *Feature reduction using OLPP*

We have to decrease the aspect of the characteristics reason for developing the accuracy. The high amount of feature is a huge problem for classification. So, feature dimension technique is implemented to decrease the features break without trailing the accuracy of classification. We reduce the amount of features and take away the unconnected, redundant or noisy information. Additionally, this extends the presentation of information classification with rapidity the processing algorithm. In this paper, we expand the orthogonal locality preserving projection (OLPP) algorithm to decrease the aspect of the characteristic vector. This OLPP algorithm varies from principal component analysis (PCA) and linear discriminate analysis (LDA). Both the algorithms intend at aspect dimensionality reduction since the initial level of the algorithm is PCA which assist in aspect fall. An adjacency chart is constructed by OLPP and the class association between the example sample points is best replicated by it. It is not simple to rebuild the data as locality preserving projections (LPP) is non-orthogonal usually. By means of Orthogonal Locality Preserving Projection technique, this difficulty is defeat which generates orthogonal basis function and can have extra locality preserving power than LPP. The sensible consequences have confirmed that OLPP has got more discriminating and defensive authority while estimated with the LPP. The Orthogonal expansion of LPP is known as the OLPP.

B) *The following procedures involved in OLPP*

The PCA is a technique that decreases data dimensionality by processing a covariance analysis between aspects. The PCA projection contains the subsequent steps: Obtain a set of features from a pre-processed data. Let x be a matrix having the size of $m \times n$.

Compute the mean value:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{2}$$

Compute the covariance matrix:

$$\eta = \frac{1}{N}\sum_{i=1}^{N} (x_i - \mu)(x_i - \mu)^T \tag{3}$$

Compute the Eigen vector e and Eigen values λ of the covariance matrix η. If η is a square matrix, a non-zero vector e is an eigenvector of η if there is a scalar λ (Eigen value) such that;

$$\eta e = \lambda e \tag{4}$$

The Eigen value and Eigen vectors are prearranged and combined. The *nth* eigenvalue communicates to the *nth* eigenvector. The conversion matrix of PCA is symbolized by T_{PCA}. By PCA projection, the extracted features are statistically uncorrelated and the grade of the novel data matrix is equivalent to the amount of attributes (dimensions).

C) *Constructing the Adjacency Graph*

Consider $X = [E_1, E_2, \ldots, E_K]$ is a set of voltage dataset. Consider G represents a graph with n nodes. The *ith* node communicates to the E_i. A boundary is place between nodes i and j, if E_i and E_j are “lock”, i.e. E_i is between p adjacent neighbours of E_j or E_j is between p adjacent neighbours of E_i. If the group information is obtainable in any two nodes we just place a border between that two nodes fitting in to the similar group.

D) *Choosing the Weights*

If i and j nodes connect to the bus, the weight W_{ij} is calculated using eq. (5).

$$W_{ij} = e^{-\left(\frac{E_i - E_j}{t}\right)} \quad (5)$$

where;
t: Constant

If the node i and j are not connected means we put $W_{ij} = 0$. The weight matrix W of graph G models have the local structure of various data.

E) *Computing the Orthogonal Basis Functions*

After discovering the weight matrix W we compute the diagonal matrix M. A diagonal matrix M is denoted as, whose entrance are column (or row) sums of W.

$$M_{ii} = \sum_i W_{ji} \quad (6)$$

After that we calculate the Laplacian matrix L using diagonal matrix M and weight matrix W.

$$L = M - W \quad (7)$$

Let $[o_1, o_2, \ldots, o_k]$ be orthogonal basis vectors, we define

$$A_{K-1} = [o_1, o_2, \cdots, o_{K-1}],\ B_{K-1}^T = A_{K-1}^T Z^{-1} A_{K-1} \quad (8)$$

where, $Z = XMX^T$.

The orthogonal basis vectors $[o_1, o_2, \ldots, o_k]$ can be computed as follows

(i) Compute o_1 as the eigenvector of $Z^{-1}XLX^T$ associated with the smallest eigenvalue.

(ii) Compute o_k as the eigenvector of associated with the smallest eigenvalue of J_k.

$$J_k = \{I - Z^{-1} A_{K-1} B_{K-1}^T\} Z^{-1} \{XLX^T\} \quad (9)$$

F) *OLPP Embedding*

Let $T_{OLPP} = [o_1, o_2, \cdots, o_l]$ embedding is follow:

$$Y \rightarrow XT^T \quad (10)$$

$$T = T_{PCA} T_{OLPP} \quad (11)$$

where;

$T \rightarrow$ transformation matrix
$Y \rightarrow$ one dimensional representation of X

This transformation matrix decreases the element of the attribute vectors of the voltage sag prediction data sets. This element decreased characteristics, given to the categorization method.

3. Proposed Algorithm

A) *Tree fuzzy rule based classifier*

Fuzzy rule based classification is a technique of producing a diagram from a specified input to an output using fuzzy logic. After that, the mapping provides a foundation, from which choice can be produced [14-15]. Membership functions, logical operations, and If-Then rules are utilized in the fuzzy rule based method. The steps of fuzzy are,

- Fuzzification
- Fuzzy Rules Generation
- Defuzzification

B) *Fuzzification*

Throughout the fuzzification progression, to change the crisp input into linguistic variables are transformed into fuzzy. The progression of fuzzification is calculated by implementing the subsequent equations.

$$ML = \min + \left(\frac{\max - \min}{3}\right) \quad (12)$$

$$XL = ML + \left(\frac{\max - \min}{3}\right) \quad (13)$$

where, ML- minimum limit values of the feature M and XL- Maximum limit values of the feature M.

By use these equations (12) and (13), to compute the minimum and maximum limit values. And also, and these regulations are supplied to produce the fuzzy values. These rules are given in to the cuckoo search.

C) *Cuckoo search algorithm*

Cuckoo search algorithm is a meta-heuristic algorithm which was presented by the reproduction activities of the cuckoos and reduces to carry out. They contain many nests in cuckoo search. Every egg point to a resolution and an egg of cuckoo specify a fresh explanation. The new and improved explanation is replacing the majority useful explanation in the nest. The following representation system is selected by cuckoo search algorithm: Every egg in a nest symbolizes an explanation, and a cuckoo egg symbolizes a novel explanation. The intent is to utilize the novel and probably improved egg to restore a not-so-good egg of cuckoo in the nests. Though this is the fundamental situation which means one cuckoo for each nest, but the amount of the method can be amplified by integrating the possessions that every nest can have more than one egg which corresponds to a set of explanations. The procedure of clustering is indicated below;

- The Only one egg at a time is laid by cuckoo. Cuckoo dumps its egg in a randomly chosen nest.
- The number of available host nests is fixed, and nests with high quality of eggs will carry over to the next generations.
- In case of a host bird discovered the cuckoo egg; it can throw the egg away or abandon the nest, and build a completely new nest [16-17].

D) *Steps of cuckoo search*

– *Initialization Phase*

The population (m_i, where $i=1, 2\ldots n$) of host nest is commenced randomly.

– *Generating new cuckoo phase*

The levy flights is used a cuckoo to selected at random and it generates new explanations. After that the created cuckoo is evaluated by the aim utility for finding the worth of the explanations.

– *Fitness evaluation phase*

Assess the fitness function based on the equation and after that choose the best one.

$$fitness = \begin{cases} \leq maimum \quad popularity \\ I_c = C\dfrac{dV(e,\dot{e})}{dt} \end{cases} \tag{14}$$

– *Updating new nests and eggs*

Modify the primary explanation by levy flights in which cosine transform is engaged. The superiority of the new explanation is evaluated and a nest is selected between arbitrarily. If the superiority of new resolution in the selected nest is improved than the previous resolution, it will be alternated by the new explanation (Cuckoo). Or else, the prior explanation is put to the side as the finest explanation. The levy flights utilized for usual cuckoo search algorithm is,

$$m_i^* = m_i^{t+1} = m_i^t + \alpha \otimes Levy(n) \tag{15}$$

where t is step size, and α >0 is the step size scaling feature limit. Here the entry wise product $\otimes$ is comparable to those utilized in particle swarm optimization (PSO), x_i^{t+1} and represents $(t+1)_{th}$ egg (feature) at nest (solution), $i=1,2,\ldots.m$, and $t=1,2,\ldots d$. The Levy flights utilize an arbitrary level extent which is drained from a Levy allocation. Additionally, as the difficulty is to choose or not a known characteristic, an explanation binary vector is engaged, where *1* communicates whether a characteristic will be chosen to create the novel dataset and *0* otherwise. In order to construct this binary vector, we have engaged the equation (15), which can supply only binary values in the Boolean lattice controlling the novel explanation to only binary values:

$$S(x_i^{t+1}) = \frac{1}{1+e^{-x_i^t}}$$
$$\begin{cases} x_i^{t+1} = 0 \ ; \ \ if \ \ S < rand \\ x_i^{t+1} = 1 \ ; \ \ if \ \ S > rand \end{cases} \tag{16}$$

where;

– *Reject worst nest*

The bad nests are removed in this level, depend on their option values and new ones are constructed. Afterward, depend on their suitability task the finest explanations are marked. After that the finest explanations are predictable and marked as optimal solutions.

– *Stopping Criterion*

Until the maximum iteration accomplishes this process is replicated. The optimized consequence will be inspected for to determine of software excellence. The particular procedure is apparently established in flowchart. It's exposed in below.

– *Decision tree*

Decision tree form is quick reliable, effortless to preserve and correct in the preparation data including voltage and error of voltage which quality to examination at every node in the tree. We would like to choose the quality that is mainly helpful for classifies examples, what is a high-quality quantitative quantify of the bad of a quality we will describe an arithmetical property called information increase that calculates how well a known quality divides the preparation instances based on their target classification. The dc-link current utilize this information increase calculates to choose between the candidate at every phase while increasing the tree.

The decision tree method contains build a tree to form the categorization procedure. Once a tree is constructing, it is functional to every tuple in the database and consequences in categorization for that tuple.

The subsequent problems are resolved by most decision tree algorithms.

– Choosing splitting attributes
– Ordering of splitting attributes
– Number of splits to take
– Balance of tree structure and pruning
– Stopping criteria

The dc-link current is a categorization algorithm depend on information entropy, its fundamental design is that all instances are drawn to dissimilar classed depending on dissimilar values of the state quality set; its centre is to establish the finest categorization quality form state quality sets. The algorithm decides information increase as quality collection criteria; as a rule the quality that has the uppermost information increase is chosen as the dividing quality of existing node, in order to create information entropy that the separated subsets require minimum. According to the dissimilar values of the quality, branches can be recognized, and the procedure is recursively described on every branch to generate other nodes and branches until all the examples in a branch fit in to the similar group. To choose the dividing qualities, the idea of entropy and information increase are utilized.

– *Entropy*

Given probability $p = [p_1, p_2, \cdots, p_s]$, where $\sum p_i = 1$, entropy is defined as

$$H(p|\forall i) = -\sum p_i \ell og\ p_i \quad (17)$$

Entropy discovers the quantity of array in a known database state. A value of $H = 0$ recognize a completely categorized set. The sup error the entropy, which means the better in the possible to develop the categorization

– *DC-link capacitor current information gain*

DC-link capacitor current decides the divide quality with the maximum increase in information, where increase is defined as dissimilarity between how much information is desirable after the divide. This is considered by formative the dissimilarity between the entropies of the unique dataset and the subjective amount of the entropies from each of the subdivided datasets. The formula used for this reason is:

$$G(D,S) = H(D) - \sum P(D_i) H(D_i) \quad (18)$$

Fig. 3 shows the flowchart of proposed algorithm. At the end of maximum iteration, check the final solution and whether the solution is satisfied, stop the process.

4. Results and Discussion

The proposed CSA-TFRC based DVR was implemented in MATLAB. Then, the voltage sag mitigation performance of the proposed DVR will be tested. The CSA algorithm implementation parameters are in Appendix. The implementation parameters of the proposed DVR and tested system are represented in Table 1. The fuzzy controller design parameters are tabulated in Table 2. The Simulink model of the proposed system is illustrated in Fig.4.

In Fig.4, the unbalance voltage problem is randomly occurred at 1.08 sec. Fig. 5 shows the symmetrical three phase voltage sag. The error and change of error voltage is calculated by comparing with the reference voltage signal. Then, the error and change of error voltage is applied to CSA-TFRC. Fig. 6 shows the performance of proposed method with comparison of the conventional method and neuro-fuzzy algorithm.

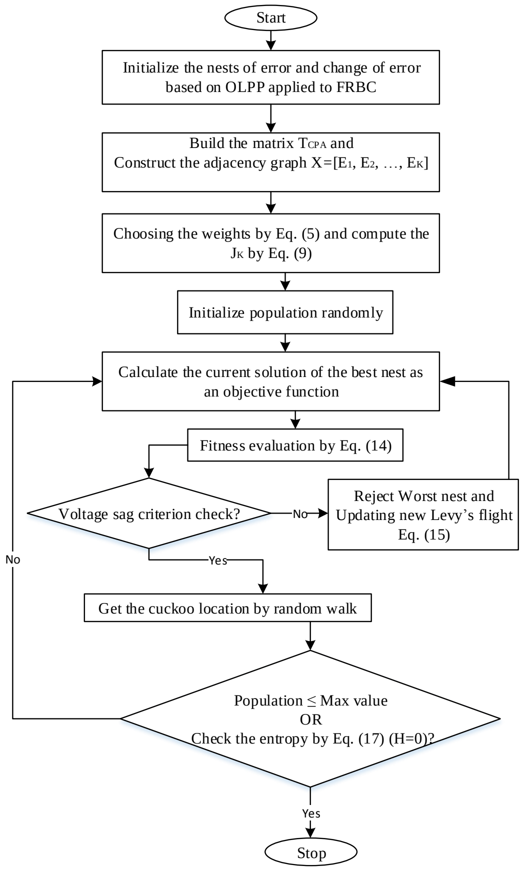


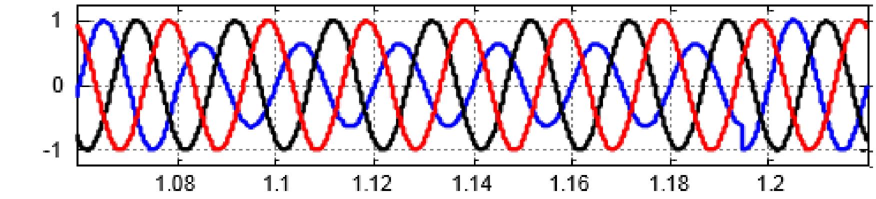
Fig.3 Proposed CSA-TFRC flowchart

Table.1.
Cuckoo search algorithm implementation parameters

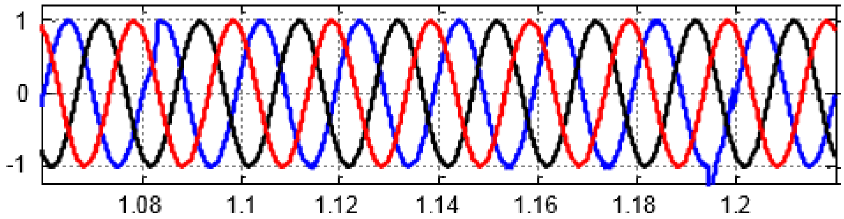
Number of nest	**5x10**
Solution space in lower bound	-100
Solution space in lower bound	100
Tolerance	$1.0e^{-5}$
Number of iteration	100
Discovery rate of solution	0.25

Table.2.
Parameters of designed fuzzy controller

Type	**Takagi-Sugeno**
Num Inputs	2
Num output	1
Num Rules	25
And Method	Min
Or Method	Max
Imp Method	Min

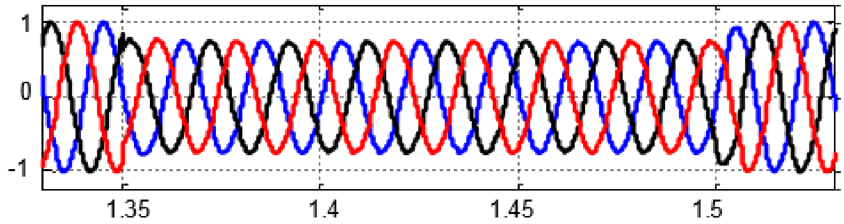


(a)

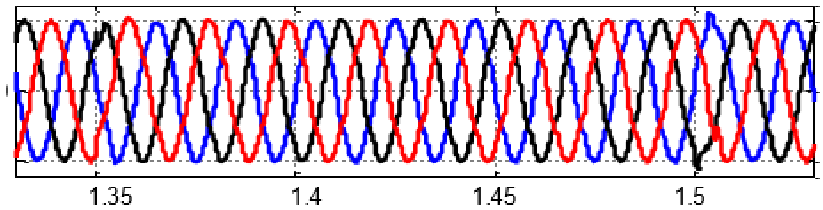


(b)

Fig.4 The p.u. voltages; (a) PCC voltage, (b) load voltage



(a)



(b)

Fig.5 The p.u. voltages; (a) voltage of PCC, (b) load voltage

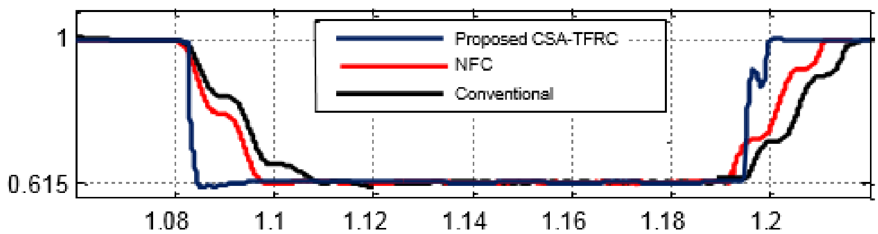


Fig.6 Estimation of voltage sag for phase A of PCC

5. Conclusion

The proposed CSA-TFRC based DVR is simulated and the performances were evaluated. For evaluating the performance of proposed DVR, the voltage sag was considered and the voltage sag clearing performance was analyzed. The voltage sag was applied randomly at different time instant and as per the variation, the regulated voltage was calculated. The comparison results show the effectiveness of the proposed algorithm over than conventional method and neuro-fuzzy method.

Appendix

Three phase Supply: 415 V, 50 Hz, Load: (1) Non Linear Load Diode Bridge Rectifier with 4 ohms 500mH on DC link (2) Linear Load: 15 Ohms

100mH, RC Filter-5 ohms and 5µF: Interfacing Inductors: 2.8 mH

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