The Use of Support Vector Machine for Phase Balancing in the Distribution Feeder

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Abstract- Phase voltage and current unbalances in power system distribution networks are major factors leading to extra losses, communication interference, equipment overloading, and malfunctioning of the protective relay, which consequently results in service quality and operation efficiency being reduced. As a better alternative to the traditional practices of manual trial and error, and the contemporary solution technique of network reconfiguration or load rearrangement, this paper investigates and proposes a novel method that is based on the use of the historical data and artificial intelligence for eliminating or minimizing phase unbalance problems. The proposed method is based on support vector machine.

Key words: Feeder load balancing; Support vector Machine

1. Introduction

The distribution system technology has changed drastically, both qualitatively and quantitatively. This may be adduced to the fact that with increase in technological development, the dependence on electric power supply has increased considerably. Consequently, while demand has increased, the need for a steady power supply with minimum power interruptions and fast fault restoration has also increased. To meet these demands, automation of the power distribution system needs to be widely adopted. All switches and circuit-breakers involved in the controlled networks are equipped with facilities for remote operation. The control interface equipments must withstand extreme climatic conditions. Also, control equipments at each location must have a dependable power source. To cope with the complexity of the distribution, the latest computer, communication, and power electronics equipment in distribution technologies are needed to be employed. The distribution automation can be defined as an integrated system concept. It includes control, monitoring and some times, decision to alter any kind of loads. The automatic distribution system provides directions for automatic re-closing of the switches and remote monitoring of the loads contributing towards phase balancing.

The phase voltage and current unbalances are major factors leading to extra losses, communication interference, equipment overloading and malfunctioning of the protective relay which consequently results into service quality and operation efficiency being reduced [2]. Phase unbalance is also manifested in increased complex power unbalance, increased power loss, enhanced voltage drop, and increased neutral current.

Traditionally, to reduce the unbalance current in a feeder the connection phases of some feeders are changed manually after some field measurement and software analysis. Although in some cases this process can improve the phase current unbalance, this strategy is more time-consuming and erroneous. In this paper, we propose the use of support vector machine based load balancing as novel procedures to perform the feeder phase balancing.

In most of the cases, the phase voltage and current unbalances can be greatly improved by suitably arranging the connection phases between the distribution transformers and a primary feeder. It is also possible to advance the phase current unbalances in every feeder segment by means of changing the connection phases [1]. The phase voltage unbalances along a feeder can also be improved in common cases by system reconfiguration, which involves the rearrangement of loads or transfer of load from heavily loaded area to the less loaded.

In the modern power distribution systems, the sectionalizing switches and the tie switches for feeder reconfiguration are extensively used [2]. The authors in [3] presented the way to control the tie switches using heuristic combinatorial optimization-based method. The only disadvantage with the tie-switch control is that, in most of the cases, it makes the current and the voltage unbalances worse. Some of the references [5, 6, 7, 8, 9] presented the use of the neural networks to find the optimum switching option of the loads among the different phases. On the basis of these results, other networks identify the radial topology satisfying the optimal condition.

In all these the phase balancing problem is mathematically formulated and then solved. The results are therefore used to initiate certain actions to eliminate or minimize the problem. With artificial intelligence it is wondered if there cannot be a simpler, more straightforward, better, and faster method. It is possible to use historical data with a more intelligent method to arrive at actions that minimize and eliminate the phase unbalance? This will not require solving a more complex problem as an intermediate step. In this paper, therefore, such a novel method is proposed by the use of support vector machine based phase balancing as procedure to perform the feeder load/phase balancing.

2. Problem Description and Mathematical Formulation

In South Africa a distribution feeder is usually a three-phase, four-wire system. It can be a radial or open loop structure. The size of the conductor for the entire line of the feeder is the same. These feeders consist of a mixture of loads, e.g. residential, commercial, industrial, etc. Single-phase loads are fed by single-phase two-wire service, while three-phase loads are fed by three-phase four-wire ($3\phi4$) service. The behavior of the load pattern (daily) depends on the function of time and the type of customers. The resulting power system voltages at the distribution end and the points of utilization can be unbalanced due to several reasons. The reasons include the following: unequal voltages magnitude at the fundamental system frequency (under voltage and over voltages); fundamental phase angle deviation; asymmetrical transformer winding impedances [9], etc. A major cause of this unbalance is uneven distribution of single-phase loads that can be continually changing across a three-phase power system due to use. Normally the consumption of consumers connected to a feeder fluctuates, thus leading to the fluctuation of the total load connected to each phase of the feeder. This in turn implies that the degree of unbalance keeps varying. The worse the degree of unbalance the higher the voltage drop and the less reliable the feeder is.

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Traditionally, to reduce the degree of the phase current unbalance, thus avoiding the malfunctioning of the protective relay and unintentional service discontinuity, the connection phases of some critical distribution transformers are usually changed manually following many field measurements and analysis. In some cases, this process certainly improves the phase voltage and currents unbalances. However, considerable time must be spent to achieve an acceptable result. In addition, the balancing status of the system, most of the time, lasts only for a short time, sometimes even only an hour. This consequence is expected because the time varying characteristic of the load is usually not considered in detail in the trial and error approach.

In general, distribution loads show different characteristics according to their corresponding distribution lines and line sections. Therefore, at the load levels, each time period can be regarded as non-identical. In the case of a distribution system, with some overloaded and some lightly loaded branches, there is the need to reconfigure the system such that loads are transferred from heavily loaded to less loaded feeders. Here the maximum load current the feeder conductor may be taken as the reference [4].

Nonetheless, the transfer of load must be such that a certain predefined objective is satisfied. The objective function can normally be defined using the property or characteristic of the problem to be solved. In this case, the objective can for example be for the ensuing network to have minimum real power loss, minimum complex power unbalance, minimum voltage drop, minimum neutral point current, or it could be to optimize the unbalance factors, or it could be weighted combination of all these.

Consequently, phase balancing may be redefined as the rearrangement of the network such as to minimize any either the total real power losses arising from line branches, the total complex power unbalance, or total voltage drop, or the neutral point current, or the unbalance factors, or the combination of all these [8].

$$f = TCPU + TPL + AVD + TVUFZ + TVUFN + NC. \tag{1}$$

Mathematically, the total complex power unbalance, may according to (2) be expressed as:

$$TCPU = \sum_{j=1}^{m} \left| V_j \times I_j^{\,*} \right| , \tag{2}$$

in which, m is the total number of feeder segments of the object feeder, V_j and I_j are the voltage and current of each segment respectively. *TCPU* can be applied to evaluate the complex power unbalance of a feeder because a lower *TCPU* means a better load balance. *TCPU = 0* Indicates the complex power at every feeder segment along the feeder is balanced.

Decreasing system loss and improving system operation efficiency are usually the major objectives of a power utility. Hence minimization of line losses is also the objective function where the total power loss may be expressed as

$$TPL = \sum_{j=1}^{m} \sum_{p=1}^{3} \left(I_j^p \right)^2 . r_j^p , \tag{3}$$

where I_j^p and r_j^p are the current and resistance of phase p of the j-th feeder segment, respectively.

Better load balance will regularly depreciate the voltage drop. Reducing the voltage drop and compressing the voltage spread are also important objectives to be achieved by distribution engineers. The average voltage drop can be evaluated as follows.

$$AVD = \frac{1}{n} \sum_{k=1}^{n} I^p \cdot Z_k , \tag{4}$$

where n is the total number of load points of the feeder.

The total current unbalance factors for zero and negative sequence labeled TCU_0 and TCU_2 are defined as follows:

$$TCU_0 = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left(I_{0,k}\right)^2} \tag{5}$$

$$TCU_2 = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left(I_{2,k}\right)^2} \tag{6}$$

The Neutral current: keeping the neutral current flowing from the common point in the wye-connection windings of the main transformer to the ground, under a specified level, is very important to avoid malfunction of the zero sequence relay. The neutral current is the summation of the three phase currents of the transformer

$$NC = \sum_{p=1}^{3} I^p \ , \tag{7}$$

in which the I^p represents the total phase current of the main transformer that feeds the consumer feeders, and *NC* is the neutral current of the main transformer.

In the proposed radial distribution system, the consumers should be connected to a phase via a selector switch as shown in Fig. 1.

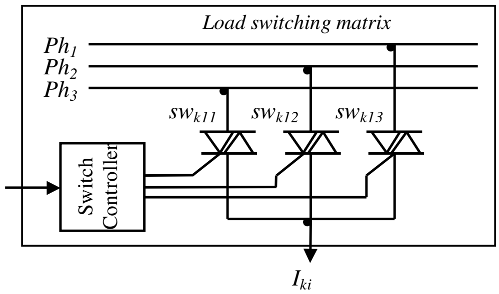

Fig.1 Switch selector

Given the topology of the selector switch, the phase current could be written as:

$$\mathbf{I}_{ph1k} = \sum_{i=1}^{3} sw_{k1i}\mathbf{I}_{ki}^{p} + \mathbf{I}_{ph1(k-1)}^{p} \ , \tag{8}$$

$$\mathbf{I}_{ph2k} = \sum_{i=1}^{3} sw_{k2i}\mathbf{I}_{ki}^{p} + \mathbf{I}_{ph2(k-1)} \,, \tag{9}$$

$$\mathbf{I}_{ph3k} = \sum_{i=1}^{3} sw_{k3i}\mathbf{I}_{ki} + \mathbf{I}_{ph3(k-1)} \,, \tag{10}$$

where $\mathbf{I}_{ph1k}$, $\mathbf{I}_{ph2k}$ and $\mathbf{I}_{ph3k}$ represent the currents (phasors) per phase (1, 2 & 3) after the k – th point of connection, $sw_{k11},\ldots,sw_{k33}$ are different switches (the value of '1' means the switch is closed and '0' means it is open). Following the constraint of allowing only one breaker in each of the equations (2) – (4) to be closed, we can write the following set of modified constraints:

$$\sum_{i=1}^{3} sw_{k1i} - 1 = 0 \tag{11}$$

$$\sum_{i=1}^{3} sw_{k2i} - 1 = 0 \tag{12}$$

$$\sum_{i=1}^{3} sw_{k3i} - 1 = 0 \,. \tag{13}$$

3. Support Vector Machine

The Support Vector Machine (SVM) is a training algorithm for learning classification and regression rules from data. The general problem with machine learning is to search, usually very large, space of potential hypotheses to determine the one that will best fit the set of data and any prior knowledge. When the data is labelled the problem is one of supervised learning in that the true answer is known for a given set of data. If the labels are categorical the problem is one of classification. When the data is unlabeled the problem is one of unsupervised learning and the aim is to categorise the data into groups with similar properties and distinct from other groups of data. The result of the learning process is known as an approximating function or alternatively as a hypothesis [9, 10].

SVMs were first introduced by Vapnik in the 1960's for classification. SVMs arose from statistical learning theory where you only solve the problem at hand without solving a more complex problem as an intermediate step. Here we focus on SVMs for regression with n inputs and n outputs. The application of the Support Vector regression (SVR) is done by the introduction of an alternative loss function. The loss function must be modified to include a distance measure. To address the issue of the loss functions Vapnik Proposed the insensitive loss function [11], which will be applied in this paper with the support vector machine, controlling the sequence of the different switches at the consumer loads for the reduction of the current and to achieve a phase balancing. The inputs to the support vector machine are load currents at each of the consumers and the outputs indicate to which phase each load should be connected, where L_{loads} represent the input data and C_{sw} the output of the support vector machine.

$$L_{laods} = \begin{bmatrix} I_{L1} \\ \vdots \\ I_{Lj} \end{bmatrix} \quad \text{and } C_{sw} = \begin{bmatrix} C_{L1} \\ \vdots \\ C_{Lj} \end{bmatrix} \tag{14}$$

The output of the network is in the range {1, 2, 3} for each load, i.e., which switch (to the specific phase) should be closed for that specific load.

3.1 Training Data

We have used the support vector machine operation for real data for 45 loads. The real data set consisted of unbalanced load data from a South African city. The test data set had average load current values per consumer in a specific locality of the city for the different times of each day in a month. We randomly selected 45 consumers as our test data for each specific time, and we tested our result on 300 data sets each of 45 loads. We consider the loads to be equally distributed per phase, i.e., we assume 15 loads to be connected per phase. So, the problem is to find the optimum sets of *n* loads, with *minimum* differences among the individual sums of the three sets.

The optimal regression function is given by the minimum of the functional.

$$\Phi(w,\xi) = \frac{1}{2}\|w\|^2 + C\sum_i \left(\xi_i^- + \xi_i^+\right), \tag{15}$$

where C is a pre-specified value, ξ_i^-, ξ_i^+ are slack variables representing upper lower constraints on the switch sequence Φ.

A non-linear model is usually required to adequately model data. In the same manner as the non-SVR approach, mapping can be used to map the data into a high dimensional feature space where linear regression is performed. The kernel approach is again employed to address the curse of dimensionality.

The above-mentioned support vector machine is then trained using the real unbalanced load as the input vector, and the output switching sequences as the target vector. Then, the network is tested with different unbalanced load data set. The output was the optimal switching sequences of {1, 2, 3} for the three-phases as explained above.

4. Simulation Results

The algorithm was tested on real data, received from local electricity supply. The test data set had average load current values per consumer in a specific locality of the city. Randomly 45 consumers have been selected as a case study. The load currents were measured at 20:00 (peak load), when most consumers are in their houses and most of the equipments used in domestic sector are on. The results are as presented in Table I. In the first column the loads are shown. In the second column switch positions for the unbalanced case are shown, and in the last two columns the SVR and neural network (ANN) balanced switch positions are shown. The last five rows in Table 1 show the total phase current for each phase, the maximum difference between the phase currents (phase unbalance) and the computational time to do the load balancing. From these results it is seen that the SVR give better results in terms of the load balancing, and the computational time is less than that of the ANN.

Table 1: 45 LOADS APPLICATION

	Unbalanced		Balanced	
		Switch	ANN	SVR
I_1(A)	40.16	1	1	1
I_2(A)	92.61	2	2	1
I_3(A)	90.77	3	3	2
I_4(A)	40.61	1	1	3
I_5(A)	88.47	2	3	2
I_6(A)	5.73	3	1	3
I_7(A)	34.93	1	3	1
I_8(A)	80.50	2	1	2
I_9(A)	0.97	3	2	3
I_{10}(A)	13.75	1	1	1
I_{11}(A)	20.07	2	3	3
I_{12}(A)	19.67	3	2	3
I_{13}(A)	59.77	1	3	2
I_{14}(A)	26.94	2	2	1
I_{15}(A)	19.68	3	2	2
I_{16}(A)	1.51	1	1	3
I_{17}(A)	73.93	2	2	3
I_{18}(A)	44.06	3	3	2
I_{19}(A)	92.24	1	1	3
I_{20}(A)	46.13	2	1	3
I_{21}(A)	41.44	3	2	2

I_{22}(A)	83.77	1	3	1
I_{23}(A)	51.99	2	1	3
I_{24}(A)	20.06	3	3	1
I_{25}(A)	66.54	1	2	3
I_{26}(A)	82.97	2	2	2
I_{27}(A)	1.94	3	3	3
I_{28}(A)	67.44	1	1	1
I_{29}(A)	37.56	2	1	2
I_{30}(A)	82.34	3	1	1
I_{31}(A)	94.06	1	1	3
I_{32}(A)	22.88	2	2	3
I_{33}(A)	60.07	3	1	2
I_{34}(A)	48.11	1	3	1
I_{35}(A)	88.23	2	1	2
I_{36}(A)	75.44	3	1	1
I_{37}(A)	45.19	1	2	1
I_{38}(A)	1.83	2	3	2
I_{39}(A)	81.31	3	2	3
I_{40}(A)	60.92	1	1	2
I_{41}(A)	78.40	2	3	3
I_{42}(A)	91.25	3	2	1
I_{43}(A)	73.08	1	2	1
I_{44}(A)	17.45	2	2	2
I_{45}(A)	44.02	3	1	3
I_{ph1}(A)	-	822.1	746.1	783.7
I_{ph2}(A)	-	809.9	778.5	773.1
I_{ph3}(A)	-	678.8	788.1	762.7
$\Delta I_{ph\text{-}max}$(A)	-	143.3	42	21
T_C(sec)	-	-	0.2	0.07

5. Conclusion

Phase and load balancing are important complements to network and feeder reconfiguration. In distribution automation these problems have to be continuously solved simultaneously to guarantee optimal performance of a distribution network. In this paper the phase balancing problem at the distribution transformers in a radial structure, and the load balancing along a LV feeder have been formulated as current balancing optimization problems with due consideration for the various constraints using the SVR models. The SVR model achieved a good load balancing result.

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