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Abstract—**Protection is the last obstacle to realizing the idea of microgrid. Some of the main challenges in microgrid protection include topology changes of microgrid, week-infeed fault, bidirectional power flow effects, blinding of the protection, sympathetic tripping, high impedance fault, and low voltage ride through (LVRT). Besides these challenges, it is desired to eliminate the relays for distribution lines and locate faults based on distributed generations (DGs) voltage or current. On the other hands increasing in the number of DGs and lines would result in high computation burden and degradation the efficiency and accuracy of the methods that utilize all these information. This paper deals with this issue by analyzing only DGs' voltage. In the first step, a fault is detected by the voltage of each DG, then the DG with the highest voltage collapse injects 333 Hz harmonic to find another DG that the fault occurs within them. Two criteria are defined in such a way to prevent injection of voltage harmonic by the other DGs. Finally, the fault is located in the reduced space of search by wavelet transform and optimized multiclass support vector machine (M-SVM). In the simulation results, the contribution of this method is shown and results also validate the efficiency of the proposed method.**

Index Terms—*Fault detection, fault location, harmonic injection, support vector machine (SVM), wavelet transform.*

I. INTRODUCTION

Microgrid (MG) consists of distributed energy sources (DERs), distributed storages (DSs), and distributed loads (DLs), which can operate in islanded and grid-connected modes [1]. Many researchers have attempted to address many technical issues of MG such as power quality, energy management, networked control, communication systems, and protection for paving the way of implementation of the MG. Among them, protection of MG is one of the most critical challenges for the realization of MG [2]-[3].

Protection of microgrid encounters several challenges including resetting of relays due to topology changes of microgrid, blinding of protection, sympathetic tripping, and week-infeed loop fault [4]. Several approaches such as limiting DG capacity [5], fault current limiter (FLC) [6], utilizing storages, modification of DG's control [7], signal processing-based methods [8], and adaptive protection [9]-[11] have been proposed to cope with these problems. The main drawback of these methods is respectively, preventing high penetration of DGs, additional cost for DGs, high investment cost, difficulty in control of the fault current, high computation burden, and high complexity. In addition, according to the complexity of the future grid, employing a directional overcurrent relay was suggested by [12] to deal with the problem of bidirectional power flow. However, this type of protective device is expensive and requires more complex coordination methods. Distance relay operates based on measuring the apparent impedance from relaying point [13]. The advantage of this relay is insensitive to source impedance, whereas, the performance on this relay is deteriorated by power swing, load enrichment, infeed effect, and high impedance [14].

Recently, as communication system has become a vital part of the power system, applications of communication assisted-based relay protection have been applied to directional overcurrent relay [15], differential relay [16] and wide-area protection [17]. On the other hand, in MG the protection relays are implemented in the distribution generations (DGs) and important loads but there is no relays for transmission line [18]. In [18], relays for distribution lines had been eliminated and the fault was located based on an approximated linear relationship between of maximum oscillation of magnitude of the transient voltage signal. However, this strategy is not applicable to locate a fault in the looped MG. In [19], an intelligent-based differential method was proposed for MG protection. As all distribution lines are equipped with differential relays, the cost of implementation is high. In [20], overcurrent relays are designed based on zero- and negative sequence analyzer and wavelet transform to detect and classify the faults.

In this paper, a novel protection strategy is proposed to locate the fault in the looped MG only by measuring the voltage at the buses of DGs. First, each DG detects the fault based on the wavelet transform and support vector machine (SVM), then in order to confine the space of search, the converter that experiences the lowest voltage amplitude generates 333 Hz voltage harmonic. The DG with the lowest 333 Hz harmonic is chosen as another candidate that fault occurs between them. Finally, the faulted section is determined based on wavelet transform and optimized multi-class support vector machine (OMSVM). Simulation results on grid-connected MG are also presented to validate the efficiency of proposed method.
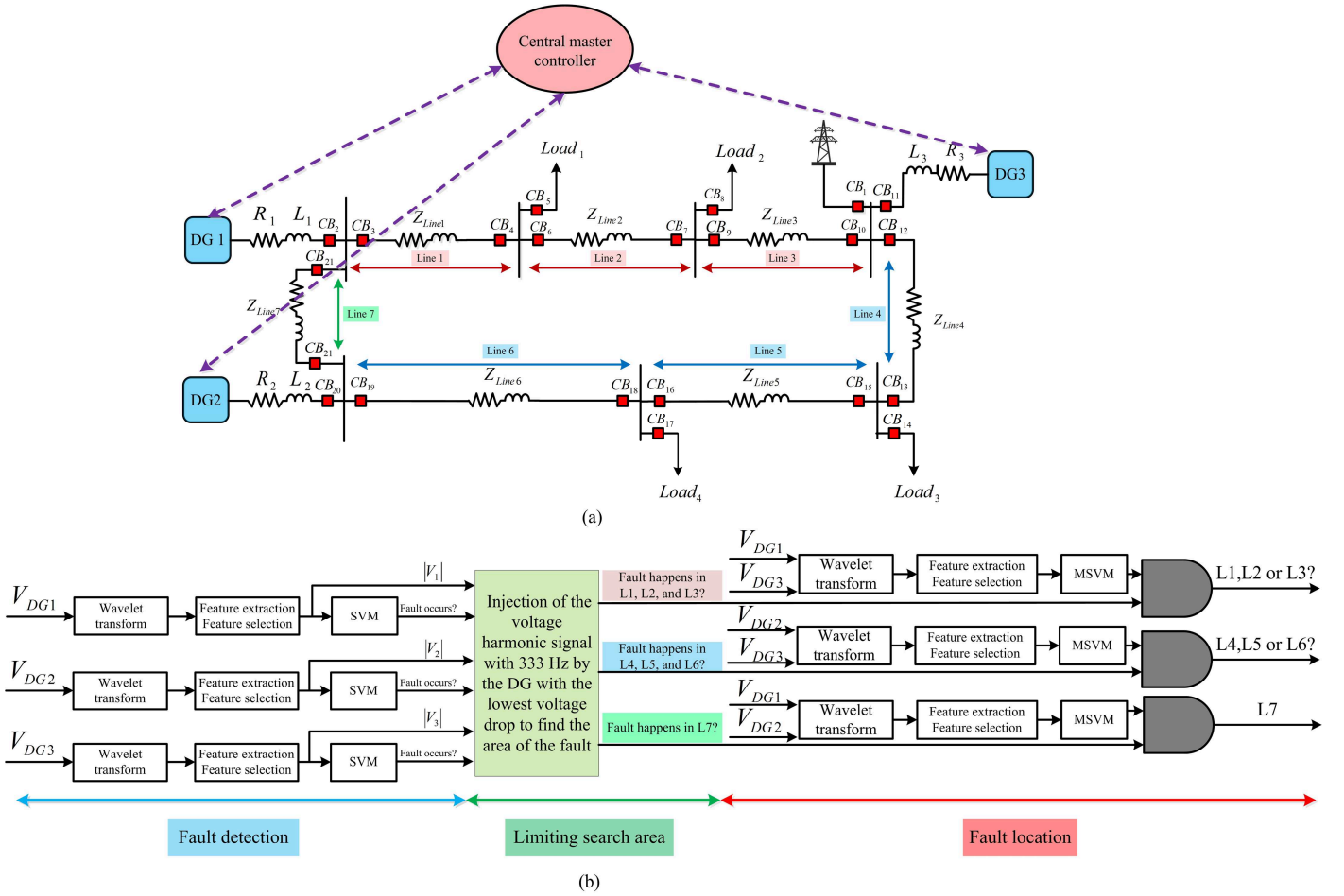
Fig. 1. Scheme of the looped microgrid and structure of the proposed protection method. (a) Model of simulated loop microgrid, (b) implemented the proposed method for the looped microgrid.

II. PROPOSED METHOD

In the proposed method, the fault is detected and located based on only the measured DGs' voltages. The benefit of this method is that there is no need to implement relays for the each line. Then, an advanced signal processing method based on wavelet transform (WT) and optimized two/multi support vector machine (OSVM) is proposed for the purpose of fault detection or fault location [18],[21]-[22]. However, for a system with high penetration of DGs, the tremendous amounts of data gathered from DGs have to be analyzed to locate the fault. Such a method is not applicable because it requires a powerful processor and the accuracy of fault location will be decreased when gathered information gets higher. To address this issue, this paper proposes a method based on injecting high-frequency voltage to confine space of solutions from the whole area to the area between two DGs. Fig. 2 shows that the proposed method, which is applied for a looped microgrid, classifies into the three stages. In the first stage, the occurrence of the fault is detected by WT and OSVM. If the fault happens, the DG with the lowest voltage magnitude will inject 333 Hz voltage harmonic to find another DG, which the fault occurs between these two DGs. Finally, in the last stage faulted section is determined by WT and optimized M-SVM.

The proposed method, which applied to the system, is presented in Fig. 1.

A. Advanced signal analysis

$$f(t) = \sum_k C_0(k)\varphi(t-k) + \sum_k \sum_{j=1}^{J-1} d_j(k) 2^{j/2} \psi_j(2^j t - k) \quad (1)$$

The relationship of scaling function and wavelet function with two cascaded resolution levels j and $j+1$ using MRA is defined as follows:

$$c_j(k) = \sum_m h_0(m - 2k)c_{j+1}(m)$$

$$d_j(k) = \sum_m h_1(m - 2k)c_{j+1}(m) \quad (2)$$

where h_0 and h_1 are low-pass and high-pass filters, respectively. As a result, by using multiresolution analysis (MRA) concept a complex signal maps into series of different resolution levels:

$$C_{Signal} = [c_0, d_0, d_1, \ldots, d_{j-1}] \quad (3)$$

where c_0 and d_j denote last approximate coefficient and detail coefficient at different resolutions levels.

In the next step, several features include mean, standard deviation, skewness, kurtosis, RMS, form-factor, crest factor,

energy, Shannon-entropy, log energy entropy, Interquartile range, clearness factor, and shape factor are extracted from the each of resolution levels [23].

B. Optimized support vector machine

The SVM is a powerful method for classification based on setting classification boundaries in such a way that the distance from closest data become maximize. This concept can be presented as follows:

$$min \left\{ \frac{1}{2} \|\omega\|^2 + C \sum_{i=1}^{n} \varsigma_i \right\}$$
S.t. $y_i(\omega^T \phi(x_i) + b) \geq 1 - \zeta_i, \zeta_i \geq 0, y_i = \{-1, +1\}^n,$
$\forall i = 1, 2, ..., n$ (4)

where ζ, C, $\varphi(x_i)$ and y_i are violation the separating hyperplane, penalty factor, a function that maps the testing data vector x_i onto high-dimensional feature space, respectively. The dual form of (4) is as follows:

$$min \left\{ \frac{1}{2} \sum_{i=1}^{n} \sum_{i=1}^{n} y_i y_j \alpha_i \alpha_j K(x_i, x_j) - \sum_{i=1}^{n} \alpha_i \right\}$$
Subject to $\sum_{i=1}^{n} \alpha_i y_i = 0, 0 \leq \alpha_i \leq C \ \forall i = 1, 2, ..., n$ (5)

where $K(x_i, x_j)$ is a kernel function that is defined as follows:

$$K(x_i, x_j) = e^{-\gamma \|x_i - x_j\|^2}, \gamma > 0$$ (6)

Although SVMs were first proposed for binary classification, they can be extended for multiclass problems. Typically, there are the common kinds of methods for addressing MSVM: one-against-all, one-against-one (OAO), and one-step. Among them, OAO has roughly more accuracy and low computation burden [24]. In OAO n(n-1)/2 classifiers are constructed and trained for two classes, then the vote for *ith* class is increased by one otherwise *jth* class is added by one. Finally, the class with the highest vote wins.

According to (5) and (6), C and γ need to be selected properly to give high accuracy estimation of SVM classifier. In this paper, adaptive fuzzy particle swarm optimization (FAPSO) algorithm is used to solve (5).

PSO is based on simulation of a flock of birds searching for food. In this simulation, each bird has its own velocity; however the movement of others can affect an individual bird's velocity and direction. This is usually dependent on one or another of the following behavioral stimulants: inertia, cognitive stimulant, and social stimulant. According to the discussion above, the mathematical model for PSO is as follows:

$$V_i^{t+1} = \omega \times V_i^t + C_1 \times rand_1(.) \times (Pbest_i - X_i^t) + ...$$
$$C_2 \times rand_2(.) \times (Gbest_i - X_i^t)$$ (7)
$$X_i^{t+1} = X_i^t + V_i^{t+1}$$
$$i = 1, 2, 3, ..., N_{swarm}$$

where C_1, C_2 are called learning factors and ω is inertia weight. In an original PSO algorithm, the above parameters hold constant. Inertia weight controls the next iteration speed. C_1 is considered a cognitive parameter due to its ability to follow its own best value; however, C_2 is for tracking Gbest. By utilizing the fuzzy system the learning factors and inertia weight can be properly determined based on the number of best fitness (BF) and the number of unchanged fitness (NU). The BF value determines performance to identify the best candidate to

represent a solution found so far. In order to apply BF to a fuzzy system, this parameter should be normalized using the following formula:

$$NBF = \frac{BF - BF_{min}}{BF_{max} - BF_{min}}$$ (8)

where, BF_{max} BF_{max} and BF_{min} BF_{min} are maximum and minimum values of best fitness value. NU value is also normalized in a similar way. The output of the fuzzy system is C_1, C_2 and ω. These parameters are confined in the range as follows: $.2 \leq \omega \leq 1.2$ $.2 \leq \omega \leq 1.2$ and $.2 \leq C_1, C_2 \leq 1.2$.

Fuzzification of the fuzzy system is done by the triangular and trapezoidal membership functions. In the inference engine, fuzzy rules can be determined according to the following expressions [25]:

I.   When best fitness (BF) is found at the end of the run, higher learning factors and a lower inertia weight is desired.

II.   When the best fitness does not change during a run, the learning factors should be increased and the inertia weight should be decreased.

C. Voltage harmonic injection

In [18],[21]-[22], whole measured data was considered for the task of fault detection or fault classification. However, the computation time will dramatically increase for a large system and correspondingly higher computation time is required for analyzing. On the other hand, the methods based on utilizing voltage sensors have the problem of multiple fault-location estimations in the looped microgrid. Because two fault points are suggested for a specific voltage drop [18],[26]. In this paper, a new method based on voltage harmonic injection is proposed to confine whole search space to the area between two DGs. The first DG is selected based on the fact that the DG bus, which is closest to the fault, has the highest voltage drop [27]. Then this DG injects voltage harmonic with the frequency of 333 Hz to detect another DG candidate. As the harmonic current has two paths to the location of the fault, the DG with the lowest amount of 333Hz voltage harmonic is chosen as another DG candidate. Fig. 2 shows this concept in the grid-connected looped microgrid. In this mode, the loads and grid are modeled as grounded impedance, whereas DGs operate based on the current-control mode (CCM) is modeled as an open-circuit connection for high-frequency disturbance [28].

Voltage harmonic with the frequency of 333 Hz is selected based on criteria such as not having interaction with the LCL filter resonant frequency, grid resonant frequency, and fundamental-frequency dependent harmonics (e.g. -5th, 7th, and so on) [28]. In addition, DG will inject voltage harmonic with magnitude of 10 V, if the following requirements are satisfied:

1. $|V_{fund}| \times 0.0005 \leq t_{injection} \leq 60 \ ms$

2.   If the DG measures voltage harmonic before voltage harmonic injection. It is not allowed to inject harmonic.
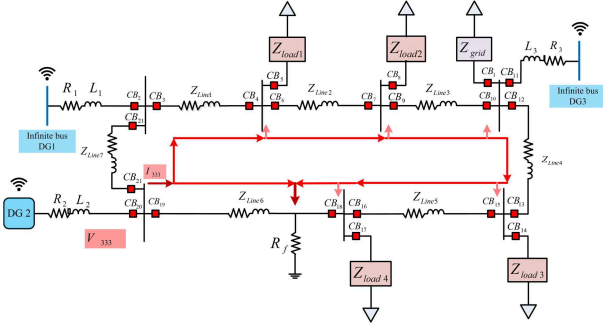
Fig. 2. Model of grid-connected looped microgrid during injection of voltage harmonic.
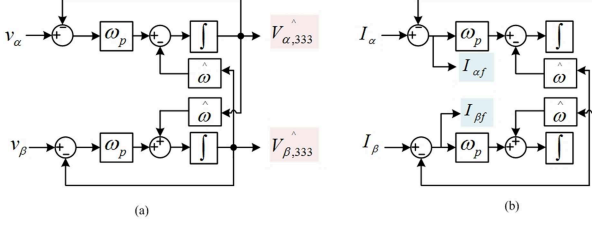

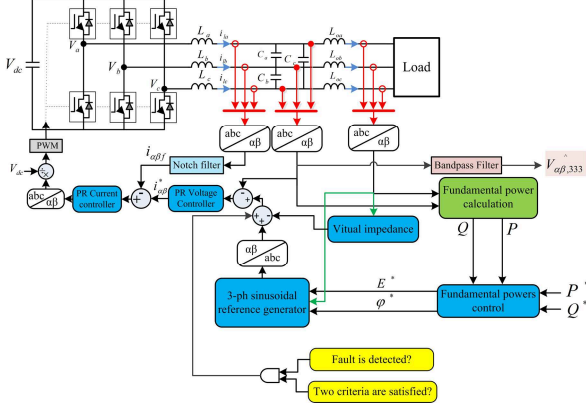Fig. 3. Applied filters: (a) Bandpass filter (b) Notch filter.

Fig. 4. The strategy of injecting harmonic for the DG.

The first criterion results in the injection of the voltage harmonic at the maximum of 60 ms and the DG with higher voltage drop will more quickly inject voltage harmonic. According to the second criterion, whenever one DG injects voltage harmonic, it prevents other DGs from voltage harmonic injection.

Although bandpass filter is designed to measured voltage at 333 Hz, a notch filter is required to prevent current control to compensate voltage harmonic. The structure of these filters and how they are applied in the control system are presented in Fig. 3 and Fig. 4, respectively.

where, $\hat{\omega}$ is frequency angle for the frequency of 333 Hz and ω_p is cutoff frequency.

III. SIMULATION RESULTS

The looped microgrid (Fig.1 (b)) with the parameters of [29] was simulated to validate the effectiveness of the proposed method.

In order to train the SVMs, different amounts of fault resistance and fault locations are considered. Then, wavelet transform decomposes signals to the six levels of details and one level of approximation. For example for a fault occurred in line 6, the voltage of DG2 besides its wavelet coefficients are shown in Fig. 5. Then, thirteen features are extracted from each level. Finally, among all the features, the best set of features is selected.
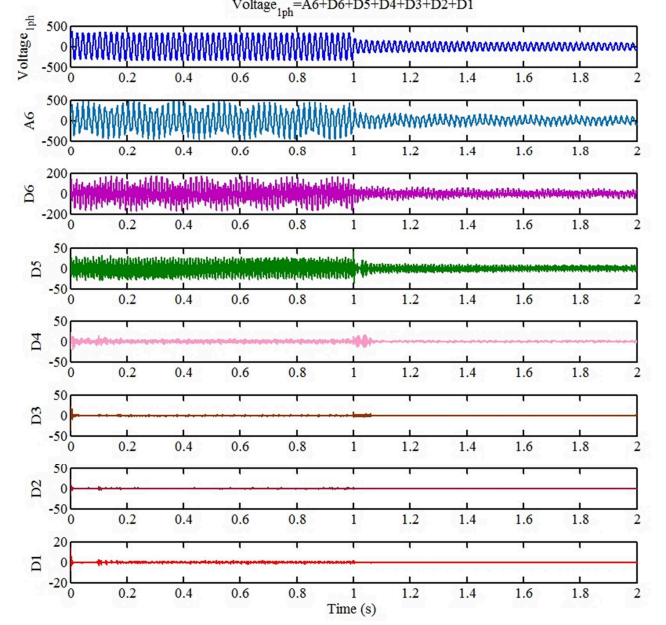

Fig. 5. Wavelet transform on one sample voltage of DG2 and their wavelet levels.
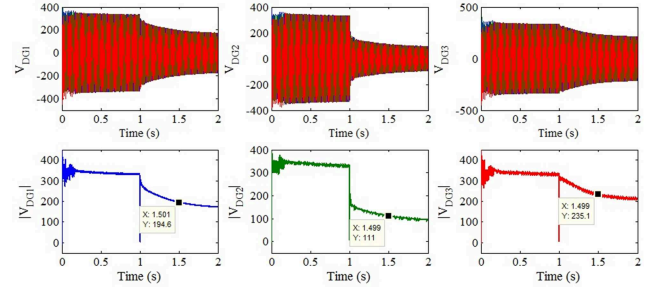

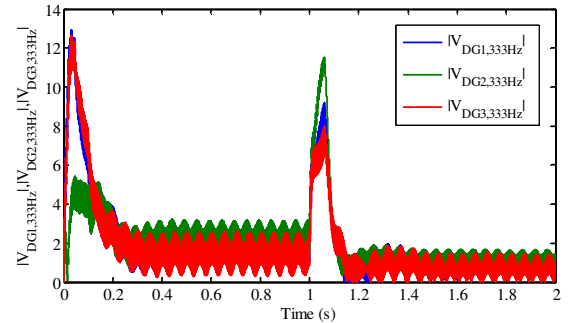Fig. 6. Probable misestimation of the conventional method based on RMS of the voltages.

Fig. 7. Voltage harmonic injection by DG2 to detect another DG with the lowest amount of measured voltage harmonic, which is DG3.
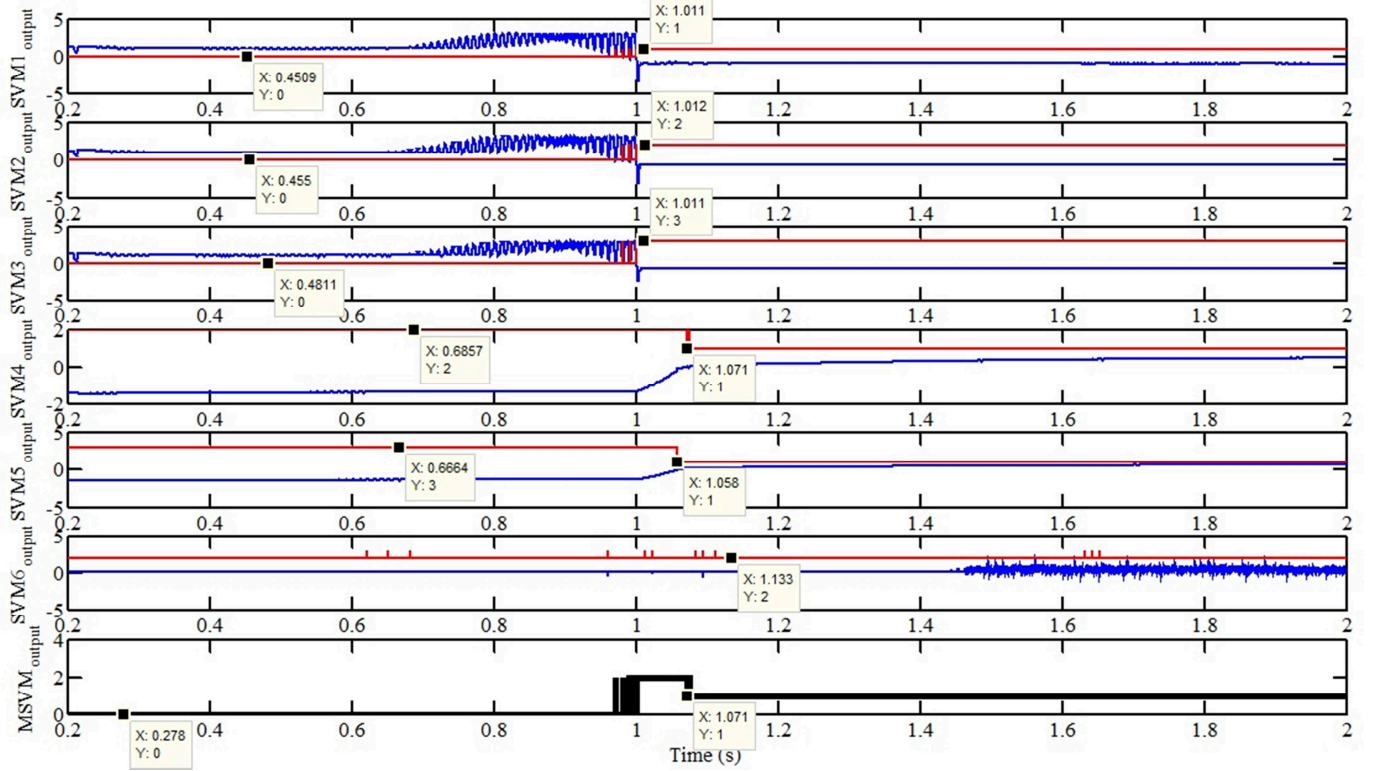
Fig. 8. Results of each two-class SVM and MSVM for the fault located in line 6.

Although the wavelet-SVM based approach is a powerful method, this method loses its efficiency in the looped microgrid. Fig. 6. Shows that for a fault located in line 6, the amount of voltage drop of DG 1 and DG 2 is lower that DG 3. As a result, the location of the fault might wrongly estimate in line 7.

Accordingly, voltage harmonic with the frequency of 333 Hz is injected by the candidate with the lowest amount of voltage. The other DGs measured this voltage harmonic to decide which of them is the next candidate that fault happens among them. Fig. 7 shows the injection of voltage harmonic by DG2, then other DGs compare their voltages and the DG with the minimum value, which is DG3, is selected as a next candidate.

In the last step, MSVM is trained for each section, which is demonstrated in Fig. 1 by blue, green, or red color. For example, MSVM utilities the extracted features from DG2 and DG3 for the purpose of fault location in the blue part encompassing line 4, line 5, and line 6. Since MSVM is built based on the OAO method, 6 SVMs is designed for the blue part. These six SVMS are defined as follows:

- SVM1: Two classes include no fault occurs (Class=+1) and the fault located in line 6 (Class=-1)

- SVM2: Two classes include no fault occurs (Class=+1) and the fault located in line 5 (Class=-1)

- SVM3: Two classes include no fault occurs (Class=+1) and the fault located in line 4 (Class=-1)

- SVM4: Two classes include fault occurs in line 6 (Class=+1) and the fault located in line 5 (Class=-1)

- SVM5: Two classes include fault occurs in line 6 (Class=+1) and the fault occurs in line 4 (Class=-1)

- SVM6: Two classes include fault occurs in line 5 (Class=+1) and the fault occurs in line 4 (Class=-1).

According to above definitions, for the fault occurs in line 6, the results of each two-class SVM and MSVM are presented in Fig. 8. In this figure, blue and red curves denote the output of SVM and its respective estimated location of the fault, respectively. Finally, MSVM calculates the location of fault based on the maximum votes algorithm. The outcome of MSVM is represented by a black curve. It can be seen that MSVM can detect and locate the fault after 70 ms.

IV. CONCLUSION

This paper has introduced and discussed a hybrid method based on wavelet transform, OMSVM, and voltage harmonic injection to locate the fault in the looped microgrid. It is shown that conventional method, which employs based one wavelet transform and MSVM, has low efficiency in detect of the fault. To cope with this problem, voltage harmonic signal with the frequency of 333 Hz is injected to confine the probable location of the fault between two DGs. Based on this method, location of the fault can be accurately estimated.

Two other advantages of this method are as follows:

- ✓ This method only relies on the voltage of DGs and there is no need of relays for distribution lines.

- ✓ As the number of the DGs increase, the number of lines or classes will be decreased. Thanks to the structure of this method the fault could be quickly detected and located in a microgrid with high penetration of DGs.

V. REFERENCES

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