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Multi SVR Approach for Fault Location in Multi-Terminal HVDC Systems

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Abstract- In this paper, a method based on machine learning strategies is proposed to address fault location problem of multi-terminal HVDC systems. Support vector regression (SVR) is employed to locate different faults in the system. The SVR is trained using extracted signatures of different voltage and current signals by utilizing wavelet transform. Two approaches are considered for applying the method to the system. The first one is the regular approach where an SVR is used for whole the line's length. A novel approach named multi-SVR approach is proposed here where, the transmission line is sectionalized and separate SVRs are applied to every section. It is shown that performance of the method is enhanced using the multi-SVR approach rather than the single SVR as every SVR focuses on smaller areas. The method performance is assessed using different simulations of a light HVDC system in different conditions.

Keywords VSC-HVDC; fault location; two-terminal HVDC; multi-terminal HVDC; Support Vector Regression; wavelet transform.

1. Introduction

Today, thanks to the advances in power electronics, high voltage direct current (HVDC) systems with long overhead lines and very long underground cables are expanding [1, 2]. These systems have some advantages such as fast and reliable control and more flexibility and efficiency. In addition, HVDC systems can be employed to connect asynchronous networks and it is one solution available for offshore wind power for long distance transmission to near shore grid [3-6]. They can maintain short-circuit level of the networks and improve stability and controllability.

Recently, with increasing demand of electrical power and penetration of renewable resources in the power systems, establishment of multi-terminal HVDC systems finds more justifications. Multi-terminal HVDC systems are generally used for offshore wind farms [7,8], underground urban distribution systems [9], shipboard power systems [10], and onshore renewable energy systems [11].

Protection of power systems against different faults is a vital issue, which is more controversial in case of HVDC power systems. For the sake of having no zero crossing, fault current interruption is a challenge in these systems. Moreover, power electronic components of these systems are susceptible to different failures in fault conditions. This is why; much research has been conducted to detect different faults in HVDC systems. In multi-terminal HVDC systems, fault location is another challenge due to presence of several lines. In these systems, it is desired that only the faulty line is disconnected from the system to preserve normal operation of the sound sections. A number of studies have been carried out for fault location of HVDC lines. As presents in Fig. 1, fault detection and location methods can be categorized into four general categories including traditional methods, signal processing techniques, intelligent methods, and hybrid methods.

In [12-14], overcurrent protection has been used to protect HVDC systems. In this approach, the system is protected after the fault detection but fault location cannot be realized. Differential protection can be used as backup protection of HVDC transmission lines [15]. In [16], a two-side current differential algorithm with a parallel communication link is proposed. An approach based on measurement of differential voltage without any communication link for MTDC networks has been proposed in [17]. However, traditional differential protection may encounter with some problems such as capacitive charging current in DC networks. Another protection method in HVDC systems is distance protection. Handshaking method is one of the proposed techniques for distance protection [18]. This method does not require communication links and it is based on local measurements of voltage and current signals. In [19], a distance protection has been proposed for HVDC systems, based on frequency dependent parameters by analyzing local measurements of voltage and current in time domain. A robust distance protection approach for VCS of HVDC system using μ synthesis analysis has been presented in [20]. Moreover, directional protection is also used to discriminate internal fault of the lines from external ones [21-23].

In [24-26], based on one side terminal data, a fault location method in HVDC transmission lines has been proposed. The method is based on calculation of time intervals between two sequential reflections of the travelling waves generated by the fault. The signals of both line's sides can also be utilized for the fault location [27, 28]. The exact instance of arriving travelling waves to the both transmission line terminals can determined using GPS-based time synchronization. In some reports, different configurations of the power systems such as combination of cable and overhead lines in the system [29] and multi-terminal systems with star connection [30] have been considered for evaluation of the travelling wave based methods. Although travelling wave based fault location methods have high accuracy, these methods have some inherent problems such as difficult wave-front identification in some conditions and the need of high sampling frequency rate [31]. In [32-35], wavelet transform has been employed to tackle some of these problems by analyzing the derived high frequency components of travelling waves. In [36] and [37], an approach based on mathematical morphology for analyzing voltage and current signals has been combined with the travelling wave method.

In [38], short-time Fourier transform has utilized to detect different fault types including AC and DC fault types accurately and quickly. Hilbert-Huang transform has also been used to extract the spectrum of transient voltages for this purpose. In [39], [40] and [41], energy of high frequency components has been extracted using Hilbert-Huang transform, empirical mode decomposition (EMD), and ensemble empirical mode decomposition (EEMD) for fault detection and location in HVDC transmission lines, respectively.

Long with existing methods, learning algorithm-based techniques can also be used as an alternative for fault location in HVDC transmission lines. In [42], wavelet transform has used to pre-process the DC voltage signal and then an Artificial Neural Network (ANN) has trained by the derived signatures for the fault detection. An overview of several intelligent algorithms for protecting the HVDC network has been given in [43]. One of the main problems of the learning based approaches is need to high amount of data for the learning and the need of updating the learning process after any change in the system. In [44], a fuzzy logic theory has been used to detect fault condition by analyzing voltage and current signals. A method based on a Support Vector Machine (SVM) has been presented in [45] for the detection. In this method, S transform has used to extract the characteristics of DC voltage signals, and then SVM has used to classify the fault. In [46], wavelet transform and SVM have used for this purpose.

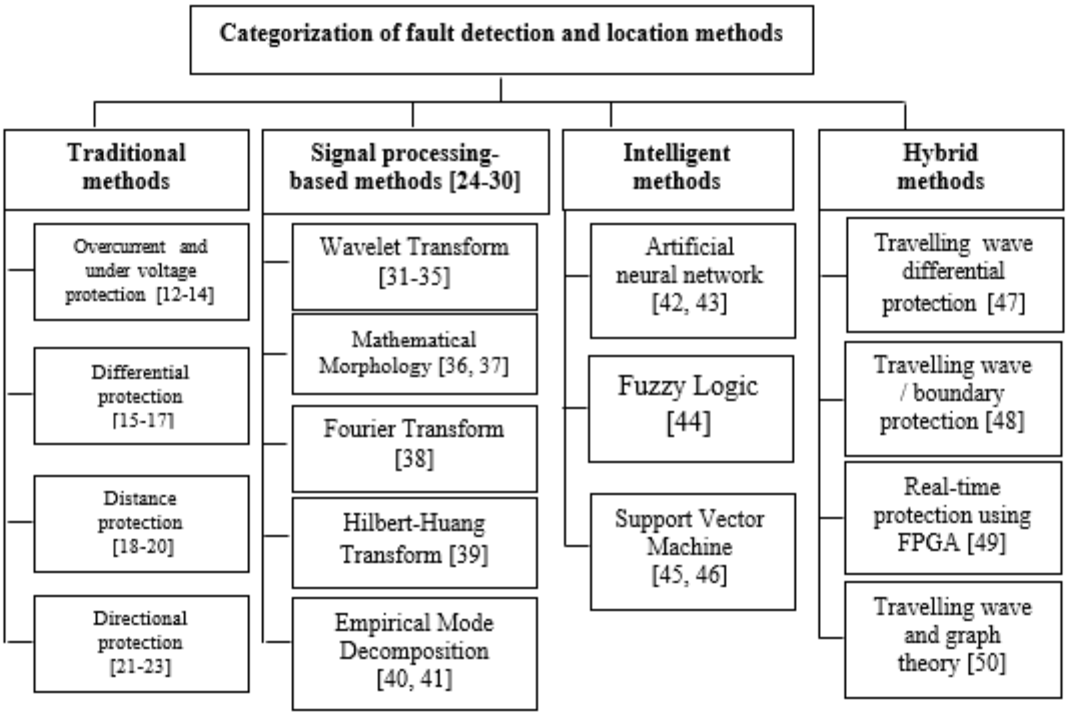


Fig. 1. Different approaches of fault detection and location.

In hybrid methods, some combinations of the mentioned methods have been addressed. For example, a travelling wave based differential protection has been introduced to protect a bipolar HVDC line in [47]. In [48], a travelling wave/boundary protection has suggested to protect a single-pole HVDC line, in which static wavelet transform has used to extract useful signatures of the DC signal. Boundary protection has also used to determine the exact internal and external faults. In [49], the real-time application of hybrid protection for a bipolar HVDC transmission line using FPGA has investigated. A combination of initial wave-front detection and graph theory has introduced for faults location in MTDC systems in [50].

According to the abovementioned discussion, each method has some advantages and disadvantages. Advantages and disadvantages of the methods are tabulated in Table 1.

In this paper, a method based on machine learning strategies for fault location in HVDC transmission lines is suggested. It should be mentioned that the concern of the paper is finding location of faults inside the HVDC lines. In facts there are protection units which detect the faults inside the HVDC lines [21-23]. The fault location unit which is the concern of the present paper, calculates the fault location after (or in parallel) with the fault detection units. In the proposed method, wavelet transform is used to extract the appropriate signatures of input signal. A support vector regression (SVR) is trained by the extracted signatures for location of faults in the system. Various input signals are considered for the learning including: 1) one-side voltage signal, 2) two-side voltage signals, 3) one-side current signal, 4) two-side current signals, 5) one-side voltage and current signals, and 6) two-side voltage and current signals. Moreover, different lengths of the analyzed window are assessed. Based on the results, the best measurement scheme, window length, and setting of the wavelet and SVR are determined. The performance of the method is evaluated by simulation of two-terminal and three-terminal HVDC systems in different conditions. Different fault locations and fault resistances are taken into consideration for the study.

In order to increase accuracy of the method, a novel approach is also introduced, called multi-SVR, in which the line is sectionalized into smaller sections and some separate SVRs are applied to each section. It is shown that performance of the method is enhanced using the multi SVR approach rather than the single SVR as every SVR focuses on smaller areas.

The main contributions of the paper are as follows:

- Fault location in multi-terminal HVDC system that far less has been dealt.
- Using multi SVR approach to have better accuracy in fault location.
- Using wavelet transform to extract the signatures of fault signal and comparison between several decomposition levels of wavelet transform.
- Using different combinations of voltage and current signals of the both line's sides as input.
- Comparison between different sampling window lengths in fault location.

2. Basis of the Method

2.1. Extraction of fault signatures using Wavelet Transform

Fast transients in the power systems appear as non-periodic signals with significant fluctuations. WT is a very powerful tool for processing these signals. Due to the ability of this transformation to analysis signals in frequency and time domains simultaneously, it can be used to process voltage and current signals and detect abrupt changes in them [51]. Wavelet transform decomposes a signal into wavelet details and approximations. On the other hands, choosing type of mother wavelet depends on type of analysis and nature of the analyzed signal. In this paper, various processes by WT have shown that Daubechies has the best results for fault location in HVDC systems.

Table 1. Advantages and Disadvantages of fault location and detection methods

Method's Name	Disadvantages	Advantages
Traditional	- Lack of selectivity - Use as back-up protection - Need for data synchronization	- Simple Technology
Signal Processing	- Difficulty of wave-front detection - Dependence on line parameters - High sampling rate, so need for expensive devises - Interference with external signals	- High accuracy and fast response - Independent of fault type and resistance, ground resistance, bus configuration and loading conditions
Intelligent	- Need to a broad learning process	- High accuracy - Fast response
Hybrid	- High volume of calculations	- High accuracy

	- Need to expensive devises for calculation	- Fast response

2.2. Support Vector Regression

Models of support vector machines are divided into two main groups: a) support vector machine classification model; and b) support vector machine regression model. Support vector machine classification model have been used to solve data categorization problems that fall into different classes and support vector machine regression model have been used to solve prediction problems. Support vector regression was introduced in 1995 by Drucker et al [52]. In this method, an error function is used that ignores errors that occur at a given distance from real values (ε) [53]. This function is defined as:

$$L\big(y, f(x,a)\big) = |y - f(x,a)|_{\varepsilon} = \begin{cases} 0 & \text{for} \quad |y - f(x,a)| \le \varepsilon \\ |y - f(x,a)| - \varepsilon & \text{for} \quad |y - f(x,a)| > \varepsilon \end{cases} \qquad (1)$$

The optimal regression function is expressed by the minimum of the following function:

$$\Phi(\omega, \xi) = \frac{1}{2}\|\omega\|^2 + C\sum_{i=1}^{l}(\xi_i^- + \xi_i^+) \qquad (2)$$

$$\text{subject to} \begin{cases} y_i - (\langle\omega, x_i\rangle + b) \le \varepsilon + \xi_i^+ \\ (\langle\omega, x_i\rangle + b) - y_i \le \varepsilon + \xi_i^- \\ \xi_i^-, \xi_i^+ \ge 0 \end{cases} \qquad (3)$$

where *C* is a predefined value, ξ_i^- and ξ_i^+ determine the upper and lower constraints of the system output, x is an input data and y is a target output and < > is internal multiplication.

The accuracy of the SVR estimation depends on the exact adjustment of the parameters ε, C and kernel parameters. For support vector regression models, various kernels are used, which are linear, quadratic, Gaussian, and polynomial. Generally, the Gaussian kernel function is better to predict performance [54]. In this paper, RBF kernel function is used to predict the fault location.

3. The Proposed Method

In this paper, two different methods for the fault location using SVR are suggested. First, in the first approach, some required input signals are measured from terminals of the HVDC system for the fault location purpose. Signatures of the faults are derived from these signals using wavelet transform. Energy of some high frequency components of the signals are calculated and employed as features for training the SVR. Flowchart of the proposed algorithm is shown in Fig. 2. In the second approach, several SVRs are employed for the fault location. The same method is utilized for training the SVRs. In this approach, each line is sectionalized into several sections and some separate SVRs are considered for the sections. Here, using an initial assessment by an SVR, the faulty section is identified. In three-terminal or multi-terminal networks, faulty line is determined by an SVR before determining the faulty section. Then, using the relevant SVR of that section fault location is determined. Flowchart of the governed algorithm for this approach in case of two-terminal and three-terminal HVDC networks is shown in Fig. 3.

So, for the large, meshed HVDC systems the proposed approach utilizes three SVR levels which are in series with each other.

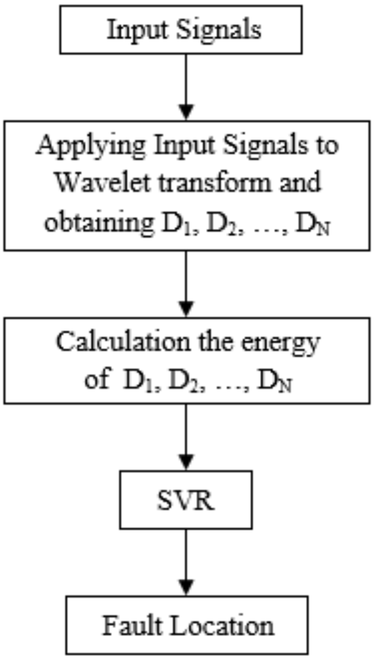
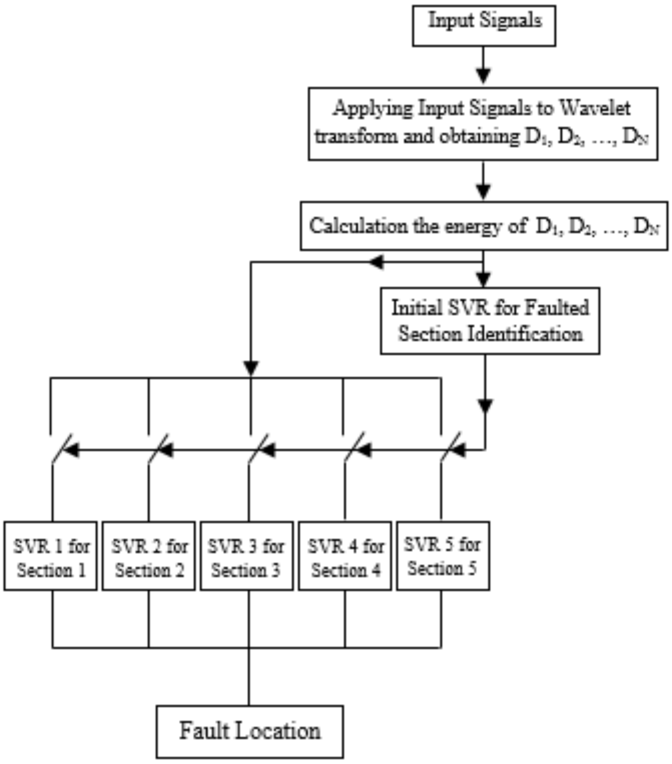


Fig. 2. Using single SVR method for fault location (N denotes number of considered details derived by WT).

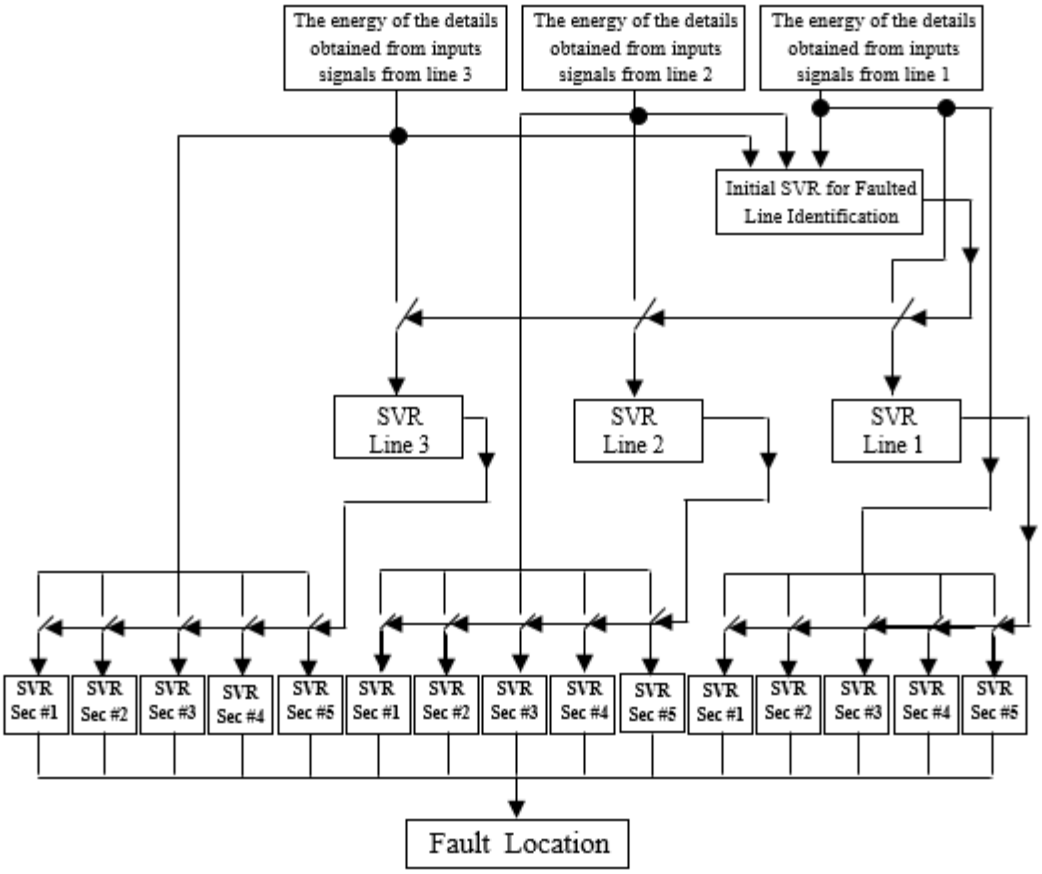
At the first level, using an initial SVR, the faulty line is identified. So even in case of large networks the first SVR only determines the faulty line. After selection the faulty line the problems is changed to a fault location problem in one two-terminal line. In the second level, another SVR which is trained by the faults inside the corresponding line, is utilized to find the faulty section. In this level which is useful for the long lines, the faulty line is sectionalized to smaller sections and the output is the number of the faulty section. In the third level, using the relevant SVR of the selected section, the accurate location of the fault is determined.

4. Results and Discussions

To test the proposed algorithm, a two-terminal VSC-HVDC network and a three-terminal VSC-HVDC network are simulated in MATLAB software, shown in Fig. 4. The main specifications of the system are 2000 MW, 230 kV AC voltage, 100 kV HVDC network voltage (Vdc), 1 kA nominal current (Idc), cable resistance of 0.014 Ω/km, cable inductance of 0.16 mH/km and cable capacitor of 230 nF/km. The cable length in the two-terminal system is 500 km. In the three-terminal system length of the first line (L_1), second line (L_2), and third line (L_3) are 200 km, 50 km and 100 km, respectively. In order to generate the required data for the training, several faults are simulated at different locations of the lines with different fault resistances. Step length for the fault location is considered as one kilometer and fault resistances are considered 0, 1, 5 and 10 Ω. After training the SVR by the gather data from M and N points in the two-terminal network or M, N, and K points in the three-terminal network, it is tested by many random faults applied to some new points of the networks.

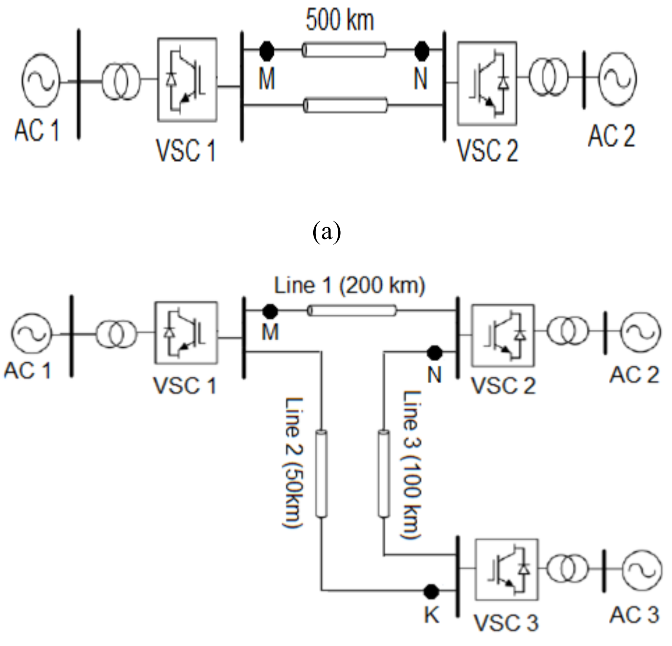


(a)



(b)

Fig. 3. Using multi SVR method for fault location in (a) two-terminal network and (b) three-terminal network.



(a)

(b)

Fig. 4. Single-Line diagram of the VSC-HVDC System (a) two-terminal system and (b) three-terminal system.

More information about the training and testing conditions are tabulated in Table 2.

The most informative frequency levels of wavelet analysis are determined by considering the sampling frequency and harmonic components appeared at different locations of the line in different simulations. According to equation (4), ten details are considered for the method as presented in Table 3.

$$f = \frac{1}{T} = \frac{v}{x} \tag{4}$$

Table 2. Other information needed to generate train and test patterns

Parameters	Value
Fault Resistances	0, 1, 5 and 10Ω
Sampling Frequency	500 kHz
Sampling Time	2 μs
Sampling Window Length	2 ms, 5 ms and 10 ms after fault occurrence
Sampling Data	Voltage and current of DC Terminals

Number of test points in two-terminal HVDC system	30 points
Number of test points in three-terminal HVDC system	23 points

Table 3. The frequency of each details and its corresponding fault location

Detail Level	Frequency of that Detail (Hz)	Corresponding Fault location (km)
D1	125000 – 225000	1
D2	62500 – 125000	2
D3	31250-62500	3 – 5
D4	15625-31250	6 – 10
D5	7812.5-15625	11 – 21
D6	3906.3-7812.5	22 – 42
D7	1953.1-3906.3	43 – 84
D8	976.55-1953.1	85 – 168
D9	488.275-976.55	169 - 337
D10	244.1375-488.275	338 – 500

In addition to these levels, some other frequency components may be appeared in the system due to the reflections. Therefore, performance of the method with some other sets of details such as D_1 to D_{15} or D_5 to D_{15} is also investigated.

Table 4 represents fault location results in the two-terminal network using single SVR method. Length of the analyzed signals, scheme of the input signals, as well as the various levels of input signal decomposition are the main indices for evaluation of the method in different conditions.

In this work, error rate of short-circuit fault location (e) is determined by

$$\text{Percentage Error} = \frac{|X_{AFL} - X_{EFL}|}{\text{Length of Line}} \times 100 \qquad (5)$$

where X_{AFL} and X_{EFL} are actual fault location and estimated fault location, respectively.

In Table 4, fault location errors for different sets of details, lengths of the selected data, and types of data are presented. For length of data equal to 10 ms, 5 ms, and 2 ms, maximum of the error are 0.9613, 2.8192 and 2.2555 respectively. Also, for these lengths, minimum of the error are 0.0045, 0.0055 and 0.0050, respectively. One can observe that among them having details of D_1 to D_{15} and using one-side current data for 10 ms after fault occurrence are the best selection. The best results in the presented tables are bolded.

Considering the best selection of the presented results in Table. 4, accuracy of the method for different settings of the SVR are presented in Table 5. It can be seen that the minimum value of fault location error occurs for values of C = 8000 and Sigma = 2.

Table 4. The percentage of fault location error results in a two-terminal network using single SVR method

Length of selected signal	Type of data	$D_1 - D_{10}$	$D_1 - D_{15}$	$D_5 - D_{15}$
10 ms	One-side Current	0.3397	**0.0045**	0.0051
	Two-side Current	0.3727	0.0172	0.0172
	One-side Voltage	0.0201	0.0241	0.0267
	Two-side Voltage	0.6852	0.8268	0.9613
	One-side Voltage & Current	0.2045	0.0145	0. 0159
	Two-side Voltage & Current	0.5804	0.4184	0.4195
5 ms	One-side Current	1.8189	0.0055	0.0063
	Two-side Current	2.8192	0.0063	0.0077
	One-side Voltage	0.1015	0.0121	0.0114
	Two-side Voltage	0.8201	1.2001	1.9567
	One-side Voltage & Current	1.1222	0.0102	2.5131
	Two-side Voltage & Current	0.6401	0.7149	0.7130

2 ms	One-side Current	0.2145	0.0050	0.0054
	Two-side Current	1.4452	0.0067	0.0067
	One-side Voltage	0.1251	0.0218	2.2555
	Two-side Voltage	1.5634	1.3214	1.1147
	One-side Voltage & Current	0.1866	0.0289	0.0141
	Two-side Voltage & Current	0.6564	0.5831	0.5838

Table 5. The average error rate of fault location results using one-side current data in different values of SVR parameters

SVR's Parameters	Error %	SVR's Parameters	Error %
C = 8000 , sigma = 2	**0.0045**	C = 1000 , sigma = 2	0.0085
C = 8000 , sigma = 3	20.5938	C = 2000 , sigma = 2	0.0075
C = 8000 , sigma = 4	23.0201	C = 3000 , sigma = 2	0.0068
C = 8000 , sigma = 5	0.0125	C = 4000 , sigma = 2	0.0063
C = 8000 , sigma = 6	4.2214	C = 5000 , sigma = 2	0.0058
C = 8000 , sigma = 7	0.0175	C = 6000 , sigma = 2	0.0054
C = 8000 , sigma = 8	0.0206	C = 7000 , sigma = 2	0.0052
C = 500 , sigma = 2	0.0106	C = 9000 , sigma = 2	0.0051
C = 600 , sigma = 2	0.0106	C = 10000 , sigma = 2	19.8531
C = 700 , sigma = 2	0.0103	C = 20000 , sigma = 2	18.7405
C = 800 , sigma = 2	0.0095	C = 30000 , sigma = 2	15.3523
C = 900 , sigma = 2	0.0088	C = 40000 , sigma = 2	91.0305

Table 6 shows comparison of the fault location results in the two-terminal network using multi SVR method and single SVR method. It is worth to mention that according to Table 4, only the 15-level decomposition has been considered. In this table, fault location errors for single SVR and multi SVR in case of different lengths of the selected data and types of data are presented. For length of data equal to 10 ms, 5 ms, and 2 ms, maximum of the error are 0.8268, 1.2001 and 1.3214 for the single SVR, respectively. Also, for these lengths, maximum of the error are 0.0740, 1.002 and 0.1013 for the multi SVR, respectively. Among all the cases, the best results are obtained in case of data length 10 ms with one side current, which are 0.0024 and 0.0045 for single SVR and multi SVR, respectively. From Table 6, it can be observed that using the multi SVR method, percentage fault location error is significantly reduced.

The fault location results for a three-terminal network using single SVR method are presented in Table 7. In this evaluation, the selected length is 10 ms, while different sets of details and different types of used signal are considered.

Here, based on the type of data and the location of it's measurement, fault location is performed for all faults occurring in the entire line. For example, in the first row, fault location has been performed using fault's signal measured from terminal M for the all faults occurring in all three lines. As observed in Table 7, by analyzing one-side current data (current of terminal M) and with details D_1-D_{15} provide the best result. However, the worst result is relevant to voltage of terminal K when details D_1-D_{10} have been used.

As mentioned, in this method the faulty line is firstly determined using an initial SVR. Then, since each line is divided to 5 equal parts, fault location and faulty section are determined using data relevant to that line and through related SVR.

Table 6. The percentage of fault location error results in a two-terminal network using multi SVR method compared with single SVR method

Length of selected signal	Type of data	Multi SVR	Single SVR

10 ms	One-side Current	**0.0024**	**0.0045**
	Two-side Current	0.0035	0.0172
	One-side Voltage	0.0172	0.0241
	Two-side Voltage	0.0740	0.8268
	One-side Voltage & Current	0.0055	0.0145
	Two-side Voltage & Current	0.0440	0.4184
5 ms	One-side Current	0.0027	0.0055
	Two-side Current	0.0025	0.0063
	One-side Voltage	0.0079	0.0121
	Two-side Voltage	0.0428	1.2001
	One-side Voltage & Current	0.0053	0.0102
	Two-side Voltage & Current	0.1002	0.7149
2 ms	One-side Current	0.0027	0.0050
	Two-side Current	0.0023	0.0067
	One-side Voltage	0.0116	0.0218
	Two-side Voltage	0.0599	1.3214
	One-side Voltage & Current	0.0093	0.0289
	Two-side Voltage & Current	0.1013	0.5831

Table 7. The percentage of fault location error results in a three-terminal network using single SVR method

Type of data and their measurement’s terminal	$D_1 - D_{10}$	$D_1 - D_{15}$	$D_5 - D_{15}$
Current of terminal M	0.0270	**0.0213**	0.0241
Current of terminal N	0.0529	0.0310	0.0423
Current of terminal K	0.1224	0.0817	0.1087
Voltage of terminal M	0.4076	0.3643	0.3657
Voltage of terminal N	0.4673	0.3991	0.4013
Voltage of terminal K	0.4954	0.4027	0.4431
Voltage and Current of terminal M	0.2412	0.1868	0.1972
Voltage and Current of terminal N	0.1650	0.1491	0.1486
Voltage and Current of terminal K	0.3680	0.2998	0.3013

Fault location results in a multi-terminal network using the multi SVR method are presented in Table 8. According to Table 4, 15-levels of decomposition is taken into account.

The results in Table 8, confirm the great superiority of the proposed approach compare to the single SVR one. As presented in Table 8, the best results for single SVR and multi SVR approaches for the three-terminal networks, which are 0.0213 and 0.0070 respectively. Also, the worst results are relevant to the case voltage of terminal K and voltage of terminal M which are 0.4027 and 0.0123 for single and multi SVRs, respectively.

The main results are presented in Fig. 5 as bar diagram to ease the comparison. All the results confirm superiority of the proposed multi SVR approach.

Table 8. The percentage of fault location error results in a three-terminal network using multi SVR method compared with single SVR method

Type of data and their measurement's terminal	Multi SVR	Single SVR	Ratio of Single SVR error to the Multi SVR error
Current of terminal M	**0.0070**	**0.0213**	**3**
Current of terminal N	0.0074	0.0310	4.2
Current of terminal K	0.0088	0.0817	9.2
Voltage of terminal M	0.0123	0.3643	29.6
Voltage of terminal N	0.0101	0.3991	39.5
Voltage of terminal K	0.0088	0.4027	45.8
Voltage and Current of terminal M	0.0034	0.1868	54.9
Voltage and Current of terminal N	0.0013	0.1491	114.7
Voltage and Current of terminal K	0.0039	0.2998	76.9

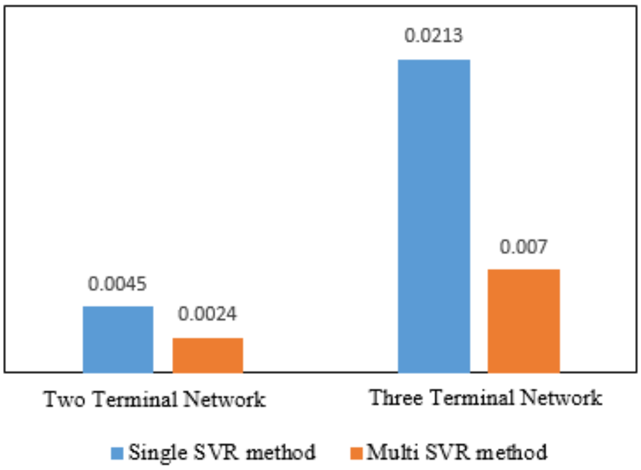


Fig. 5. A comparison between the percentage of errors of the best results of single SVR and multi SVR approaches.

5. Conclusion

A method for fault location of HVDC transmission lines based on machine learning strategies is proposed. SVR is employed for the fault location, trained by extracted signatures of different voltage and current signals using WT. The best combinations of voltage and current signals and the best setting for the SVR parameters are derived. A new approach called multi-SVR was introduced and the performance of two approaches; single SVR and multi-SVR were investigated for this purpose. Performance of both the method was evaluated using different simulations of a light HVDC system in different conditions. The minimum errors for single SVR were 0.0045 and 0.0213 which are relevant to the case with one-side current and current of terminal M for two-terminal and three-terminal networks, respectively. Also, minimum errors for multi SVR were 0.0024 and 0.0070, which appear in case of one side current and current of terminal M for two-terminal and three-terminal networks, respectively. The simulation results confirm this expectation where the multi-SVR approach has better performance, which can be a promising approach to address fault location of HVDC.

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