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Optimal Placement of Monitors in Transmission Systems Using Fuzzy Boundaries for Voltage Sag Assessment

M. Haghbin and E. Farjah

Abstract--**This paper presents a new algorithm for optimal placement of monitors in a large transmission network in order to assess voltage sags. An integer programming-based algorithm using fuzzy system is proposed for choosing the location of power quality meters. Optimization is performed by using genetic algorithm (GA). In order to show the effectiveness of proposed method, the algorithm is tested on a large transmission network (IEEE 118 bus model). Also a comparison with previous researches in this field is given.**

Index Terms-- **Fuzzy system, genetic algorithm, monitoring, power quality, voltage sag.**

I. Nomenclature

Z	Bus impedance matrix.
z_{ij}	General entry of the bus impedance matrix Z.
v_{kf}	Residual phase voltage at bus k during a fault in bus f.
V_{dip}	Matrix formed by residual voltages v_{kf}.
$MRA_{k(p)}$	Monitor reach area (set) of bus k for threshold p.
$FMRA_{k(p)}$	Fuzzy Monitor reach area (set) of bus k for threshold p.
X	A row vector in which all of its elements are binary (a 1, means the existence of a monitor and a 0 means that no monitor exist in i_{th} busbar).

Introduction

VOLTAGE sag is a short duration reduction of the rms voltage due to the short circuits, overloads or starting of large motors. A voltage dip greater than 10 percent of nominal voltage is considered as a voltage sag in IEC standard. The importance of voltage sags among other power quality effects is mainly due to its detrimental effects on several sensitive equipments. Voltage sag can happen due to the short-circuit faults, occurred hundreds of kilometers away from the point of detection. It should be noted that there are far more voltage sags than interruptions in transmission networks [1]. As a single event, voltage sag is characterized by its magnitude (the residual voltage during the event) and its duration (the time during which the rms of voltage stays below a given threshold, by definition 0.9 p.u.)[2].

Voltage sags, similar to other power quality events, should be treated as a compatibility problem between equipment and supply. When installing a new piece of equipment, a customer needs to compare the equipment sensitivity with the performance of the supply. Information about equipment sensitivity can be obtained from the manufacturer or through equipment tests. Information about the performance of the supply can be obtained through monitoring of the supply or through stochastic prediction [3],[4].

Installation of metering and monitoring systems has been growing rapidly for several reasons such as the need for automated metering and customer billing [5]. Classical monitoring in power systems is not new, but power quality monitoring is recently employed for a better assessment and analysis of steady state and transient phenomena occurred in power system due to power quality events. Although conventional monitoring devices are cheap and are installed permanently for monitoring steady state or quasi stationary quantities, accurate power quality monitors are expensive and are installed during a defined period and in certain important buses. So the aim is to install a minimum number of meters in proper buses while assuring that no essential data is missed.

To be effective, the monitoring program must be representative in time and space. At least four questions need to be answered:

- How many monitors need to be installed?
- Where should the monitors be installed?
- What voltage threshold should be set?
- How long should the monitoring program be? [6]

This paper addresses to the three first questions. An integer programming model is introduced that allows minimizing the number of meters needed to characterize a large transmission network in terms of voltage sags [7]. The optimal monitoring program determines optimal locations for meters so that the complete network could be monitored. The optimization method is implemented on a 118-bus network and solved by using a genetic algorithm combined with fuzzy logic search type algorithm. Fuzzy logic helps to evaluate optimal number of monitor and finds the best arrangement. This paper is organized as follows. In section II, a short circuit analysis on network is performed and the residual voltages in all of busbars when a fault is occurred in one specific bus could be obtained. In section III, by using the obtained data from short circuit analysis, a fuzzy boundary map for virtual monitors is proposed. Then fuzzy genetic algorithm is used to obtain the optimized number of monitors. Section IV presents the

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simulation results. In order to show the effectiveness of proposed method, the algorithm is tested on a large transmission network (IEEE 118 bus model). Finally a conclusion is given.

II. SHORT CIRCUIT ANALYSIS FOR VOLTAGE SAG ASSESSMENT

Among various causes for occurrence of voltage sags, the short circuit is the most probable. In order to generate a voltage sag on different buses of a power network, it is simply sufficient to apply a sever short circuit on one of the buses of network. By knowing the Bus Impedance Matrix *Z*, the residual voltage of any given bus in per unit, could be obtained as (1)

$$V_{dip} = \text{Ones} - Z.Inv(Diag\ (\ Z\ )) \qquad (1)$$

where, V_{dip} is dip matrix that contains residual voltage of all of buses, *Diag*(*Z*) is diagonal matrix of Z, and **Ones** is a matrix with all elements, equal to one. When a fault occurs on bus k, the voltage of other buses is stored in k_{th} column of matrix V_{dip}. So the columns of V_{dip} indicate position of the fault in network and the rows indicate residual voltage during short circuit.

III. OPTIMIZATION PROBLEM

The aim of this paper is to find an optimized monitor arrangement i.e. an arrangement with a minimum number of monitors and best points for their installations which enables a complete voltage sag supervision of whole system. It should be noted that the number of voltage sags that could be recorded by a monitor during a given monitoring time, depends on critical voltage threshold [2] defined for that monitor. If this threshold is set too low, then the meter will not capture all of important disturbances in its vicinity. On the other hands if the voltage threshold is set too high, the monitor may record a lot of non-important voltage sags which have less influences on bus bars under supervision of this monitor.

In almost all of studies published recently, a strict threshold value for discriminating the boundary around a monitor is used. Indeed, this threshold voltage determine the area of network that can be observed by a given meter But it seems that determining a strict boundary is not a practical way for real discrimination of different zones and instead a kind of fuzzy boundary seems to be more practical. The boundaries used for instance in reference [2] doesn't give any information about monitors' observation area but instead just show which busbar can be observed by which monitors and doesn't show which arrangement of monitor is most suitable for whole observation of network.

In this paper, a fuzzy threshold for discriminating the boundaries around each monitor is proposed. Of course the method gives different arrangement for placing monitors in network but by selecting a fuzzy type boundary, one can decide which minimum number of monitor is most efficient.

Crisp type boundary and fuzzy type boundary are shown in Fig.1. As shown In Fig.1(a), strict boundary just shows which busbar is in monitor observation area but fuzzy boundary in Fig1(b) shows busbars and their influence on monitor observation area. Each location in fuzzy boundary has a fuzzy degree which is determined by its fuzzy membership function and useful to show busbar location in monitor observation area.

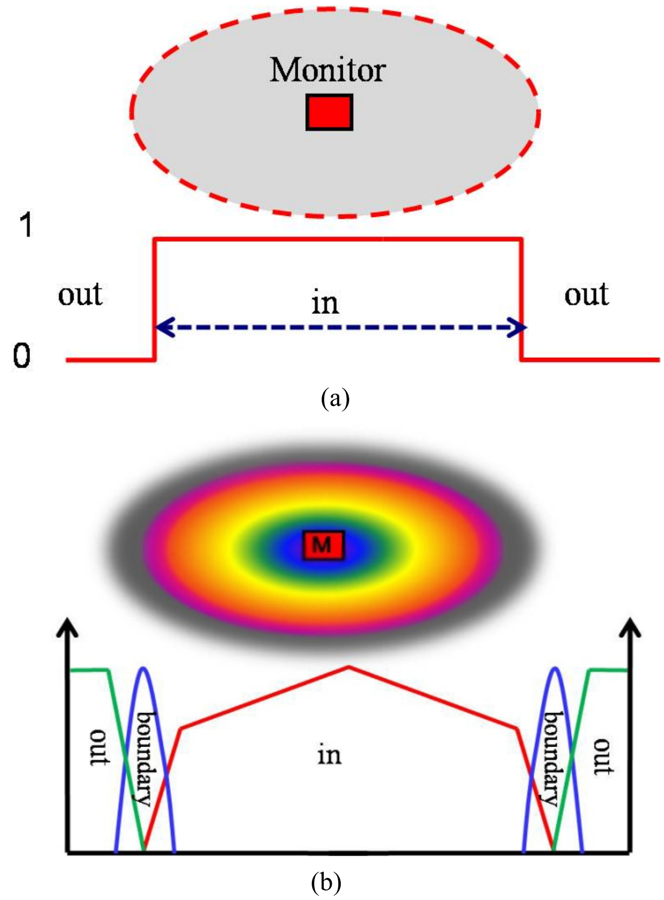


Fig. 1 Two boundary types.(a) Crisp boundary. (b) fuzzy boundary with fuzzy membership function

In order to show the advantage of fuzzy boundary consider the example shown in Fig. 2. In this figure, two monitors are able to observe network completely and we have two possible monitor's arrangements. Algorithm based on crisp boundary Fig.1(a), can't decide which monitor arrangement is better but an algorithm based on fuzzy boundary Fig.1(b) is able to decide which monitor arrangement detects voltage sags with higher accuracy. As shown in Fig.2(b), the lowest voltage sag in case of a fault on bus 26 is recorded by monitor M1 placed in bus12 and its value is 0.88 per unit. But in Fig.2(a) the lowest sag in case of a fault on bus 23 is recorded by monitor M1 placed in bus 21and its value is 0.65 per unit. Therefore sags are more observable in arrangement of Fig.2(a).

For solving optimization program, first, the concept of Monitor Reach Area and then the concept of Fuzzy Monitor Reach Area will be introduced and monitor's fuzzy boundaries in network will be determined. Finally an optimization search algorithm used to find minimum number and best arrangement of monitors in network will be presented.

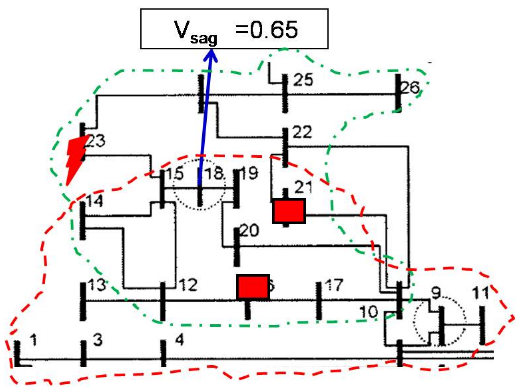
A. Finding Monitor Reach Area

The monitor reach area *MRA* is defined here as the area of the network that can be observed from a given meter position.

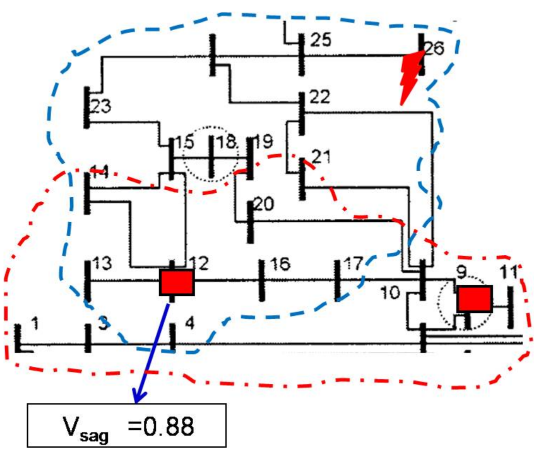
A useful way to describe all monitor reach areas is to use a binary matrix in which a 1 in entry *(i,j)* indicates that node j belongs to the MRA of a meter located at bus i with a voltage threshold p . The dimension of this matrix is N by F_p where N is the number of observation buses, and F_p is the number of fault positions. Equation (2) shows this matrix for a voltage threshold p where v_{ij} is the entry *(i,j)* of the dip-matrix described in (1).

$$MRA_p = MRA_{ij} \begin{cases} 1 & if\ v_{ij} \le p \\ 0 & if\ v_{ij} \ge p \end{cases} \qquad (2)$$

This kind of MRA is useful when algorithm want to decide how many monitors are needed for observing network completely.



(a)



(b)

Fig. 2 An example showing different proposition with same number of monitors.

Now consider a decision row vector X of length N indicating the need for a meter at a specified network's busbar. A 1 in i_{th} entry of this vector indicates that a monitor is placed at bus i and a 0 indicate the no monitor exist at bus *i*. Vector elements are calculated by (3).

$$X_i = \begin{cases} 1 & \text{if monitor is needed at bus i} \\ 0 & \text{if monitor is not needed at bus i} \end{cases} \qquad (3)$$

It is important to note that the multiplication of X times any column j of monitor reach area matrix (MRA_p), gives the required number of meters necessary for detection of sags due to fault in bus j .

Search algorithms with different constraints are used to find optimal solution among arrangement with equal number of monitors. In order to make sure that each fault is seen at least by one meter, one should check that following constraints are fulfilled:

$$MRA_{11}.X_1+MRA_{21}.X_2 \ \ldots \ MRA_{n1} . X_n \ge 1$$
$$MRA_{12}.X_1+MRA_{22}.X_2 \ \ldots \ MRA_{n2} . X_n \ge 1$$
$$\vdots$$
$$MRA_{1Fp} .X_1+MRA_{2\,Fp}.X_2 \ \ldots \ MRA_{n\,Fp} . X_n \ge 1$$

A. Finding Fuzzy Monitor Reach Area

As described before, MRA_p just show the area of the transmission network that cause voltage drop less than or equal to voltage threshold p at the meter position. Fuzzy *MRA* can also consider the distance (electrically) between monitors and fault location. A fuzzy inference system like one shown in Fig. 3, could be used to create *FMRA*. The input data is V_{dip} element and the output is fuzzy degree that shows busbar position on monitor reach area. Fig. 3 summarizes the overall procedure for obtaining *FMRA*.

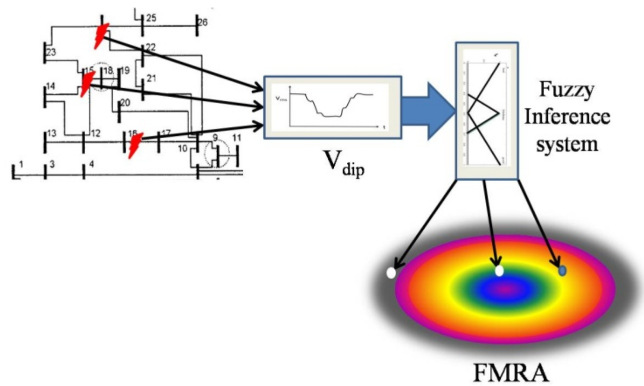
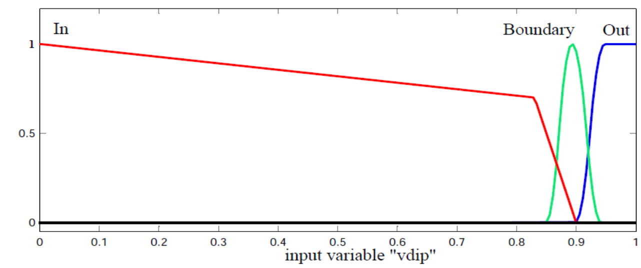


Fig.3 summarize creating FMRA in a network by use V_{dip} Matrix

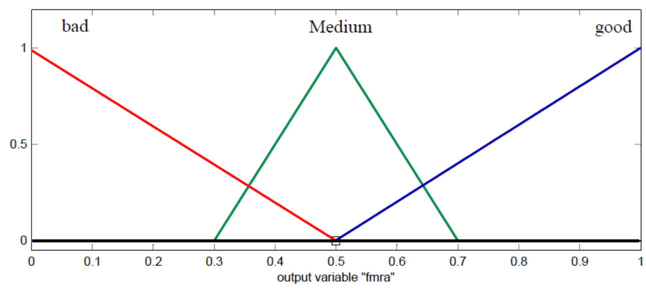
The benefit of using *FMRA* is that other than just obtaining the *MRA* for each monitor, a ranking for final optimized solution proposed by search algorithm also is gained. *FMRA* gives an effectiveness level while detecting a voltage sag for each fault positions, depending on the measured voltage drops by that monitor. The input membership function has three parts:

- *In*,
- *Boundary*
- *Out*

The first part(*In)* is assigned for busbars that are completely included in monitor reach area and as shown Fig.4, this part is represented by a very low slope line ; this small slope makes a slight difference between busbars which are positioned in reach area of monitor based on their position. For distinguishing between inner busbar and outer busbar the slope in neighborhood of boundary, drops sharply. There is a narrow region between *In* part and *Out* part because we can't specify a strict boundary for each monitor. The third part represents the buses out of monitor reach area and includes busbars with a sag more than threshold voltage. Input and output membership function has shown in Fig.4.



(a)



(b)

Fig.4 *FMRA* membership functions (a) input membership function (b) output membership function

These fuzzy inference system works with three laws as describe below:

- If (*input* is *In)* then (*output* is *Good)*
- If (*input* is *Boundary)* then (*output* is *Medium)*
- If (*input* is *Out)* then (*output* is *Bad)*

C. Fuzzy Fitness Function

As said before, genetic algorithm is one of the search algorithms that could be used for obtaining optimal number of monitors. The fitness function used in [2] just compares populations by number of their monitors and didn't give any information about their effectiveness and their observing ability. In this paper by using *FMRA,* one can influence the selection procedure not only based on number of monitors but also based on their optimal arrangement. The improvement in observing strength or ability in this paper is called *observation index* and is defined as a combination of three following factors:

- *the ability to detect maximum dip,*
- *the ability to record a less average value for sags,*
- *the ability not to miss any minimum dip*

It is obvious that a combination of these factors gives more chance to that monitor to be selected as an important monitor. Therefore even if the fault's impedances is increased which leads to a weaker sag, monitor with better *observation index* is still able to observe these weak sags and the risk of a blinded monitor is reduced. Mamdani fuzzy system with ten rules is used for calculating this *observation index* as is shown in Fig.5. Some fuzzy rules are shown as follows:

1) *If (Best is good) and (Average is good) and (Bad is good) then (output is excellent)*
2) *If (Best is good) and (Average is good) and (Bad is middle) then (output is good)*

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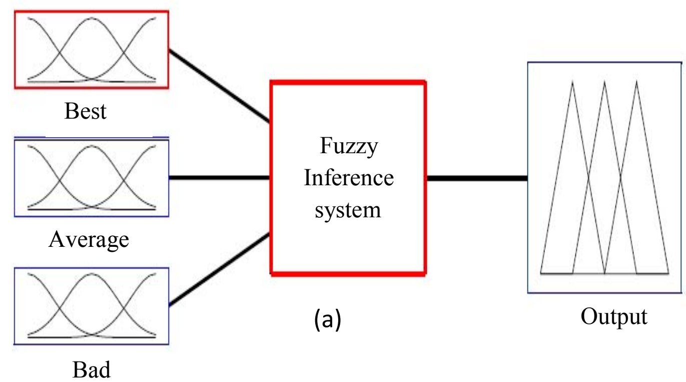
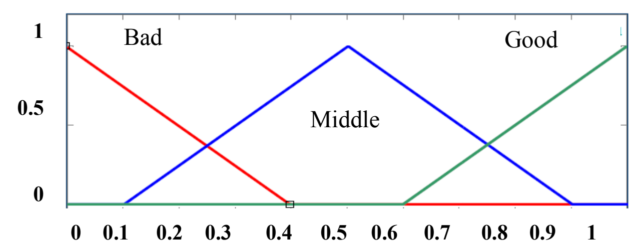
.

10) *If (Best is bad) and (Average is bad) and (Bad is* bad) then (output is very bad)

By having the number of monitors and *observing index*, one can easily select the best monitor arrangement. A fuzzy *Sugeno* system with linear output function is used as fitness function. The reason for using *Sugeno* [8] system is its ability to make linear relationship between input and output. The fuzzy inference system and input membership function are shown in Fig.6.





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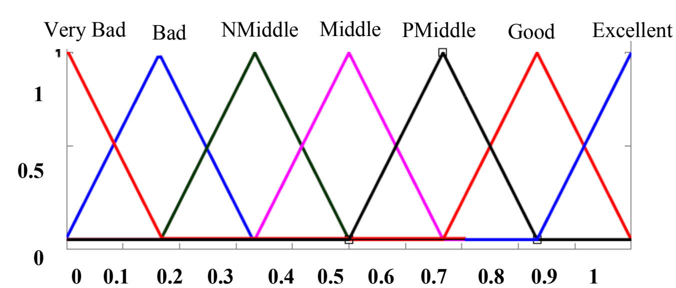


(c)

Fig.5 Fuzzy system for calculation of observation index (a) system block diagram (b) input membership function (c) output membership function

It is important to note that one should use *MRA* matrix for applying constrains because all faults should be seen at least by one meter. Flow chart describing the basic steps for optimization program is shown in Fig.7.

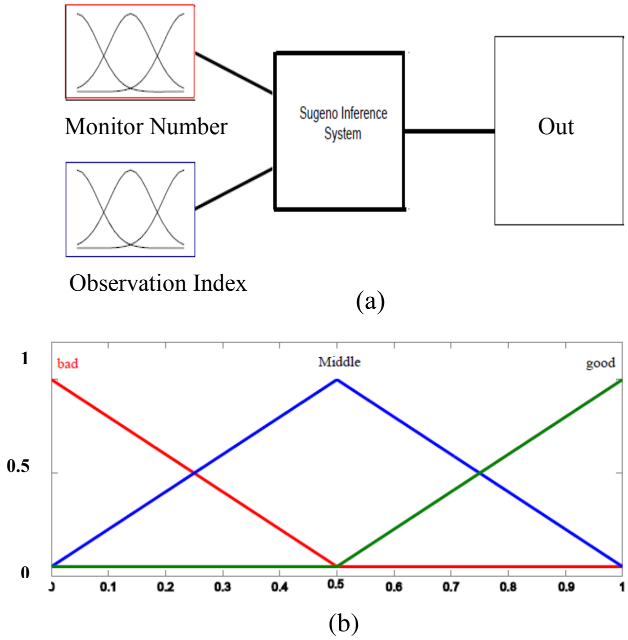


Fig.6 Fuzzy fitness function system (a) system block diagram (b) input membership function

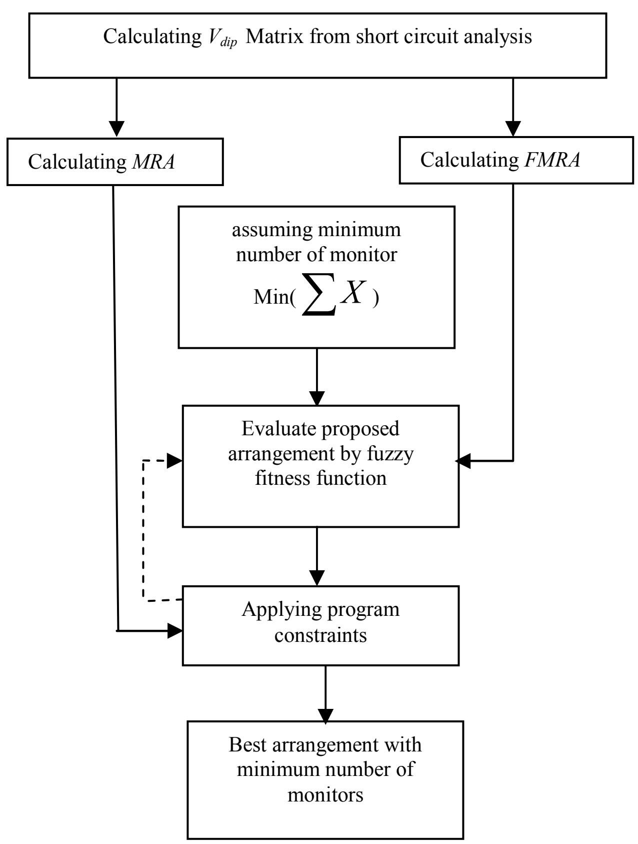


Fig.7 Flow chart of optimization program

IV. Simulation Results

In order to show the effectiveness of proposed algorithm, the method is applied and tested on IEEE 118 bus model. It is important to mention that generator's impedance affect the short circuit analysis. The generator's impedance that is used in this paper is determined according to generator output power, load flow analysis, and recommendation of [9].

The Matlab genetic algorithm toolbox is used for solving optimization program. The algorithm converges to a solution with 7 monitors. Three best arrangements proposed by this algorithm are shown in table 1.

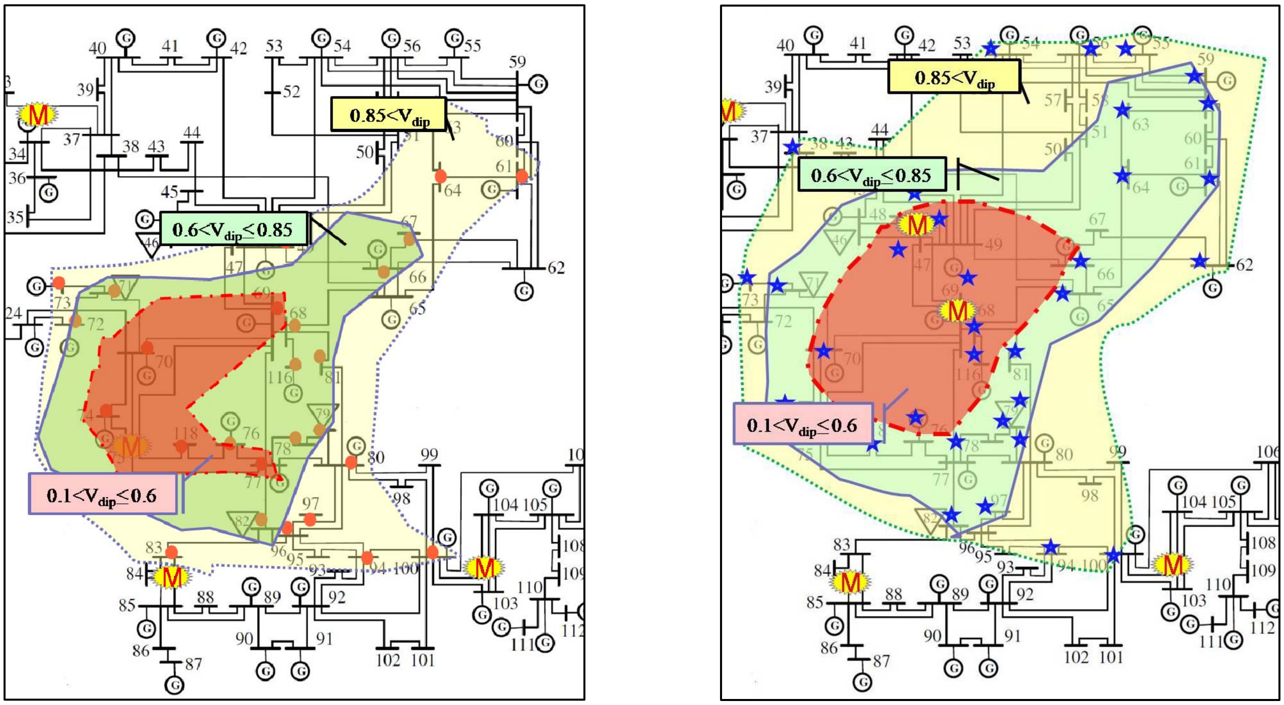
TABLE I
THE BEST MONITOR ARRANGEMENT SELECTED BY ALGORITHM IN CASE OF 7 MONITOR IN 7 BUSBAR

Monitor Arrangement Rank	**1st (The Best)**	**2nd**	**3rd**
Proposed Placement of Monitors by Algorithm (busbar's number)	5	5	5
	23	23	23
	34	34	34
	47	55	47
	69	69	75
	85	85	85
	103	103	103

As is shown in table 1, the difference between 3 best arrangements is only one monitor. For example in 1st arrangement monitor is located at 69th busbar whereas in the 3rd arrangement it is located at 75th busbar. The 1st and 3rd arrangements are shown in Fig.8 (a part of IEEE 118 bus network)

V. Conclusion

In this paper, a new technique for finding best arrangement of power quality monitors in a transmission network is presented. This technique is based on using a *FMRA* Matrix and genetic algorithm. Comparing this technique with recent works presented in literature, the fuzzy boundary concept, allows a better arrangement of monitors and improve *observation index* as presented in this paper. In order to show the effectiveness of proposed algorithm it is tested on a large transmission network (IEEE 118 bus model). As a result, it is assured that any voltage sag in the whole network will always be detected at least by one monitor and the number of monitor is kept as minimum as possible. Referring for example to simulation results obtained from case study, only 7 monitor (in 118 bus network), is sufficient for a complete assessment of voltage sag.



(a) (b)

Fig8. The observation area (a) for monitor installed at bus.69(1st arrangement) (b) for monitor installed at bus.75(3rd arrangement)
Inner region show busbars that create sag whitin $0.1<V_{dip}<0.6$ at monitor position
Middle region show busbars that create sag whitin $0.6<V_{dip}<0.85$ at monitor position
Outer region show busbars that create sag with $0.85<V_{dip}$ at monitor position

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VII. Biographies

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