

## A Novel Approach for Monitoring of Voltage Stability Margin subsequent to Observability Analysis: a Practical System Case Study

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**Abstract.** This paper presents a practical approach for voltage stability margin (VSM) monitoring in a pilot project, in which two related steps are considered. Through the planning stage of a practical project, it is necessary to make the grid observable to actualize the VSM monitoring during the operation. So, an observability based VSM monitoring scheme is proposed in this work. Firstly, using observability analysis and state estimation requirement, optimal location of metering devices is determined for the Hormoz distribution grid as a practical system case study. Secondly, using the information sent by metering devices, the VSM monitoring is evaluated using a transfer function (TF) model during the operation. To assess the performance of the proposed method, it is compared with a case, in which metering infrastructures are connected to the whole of buses. For further simulation, input data combinations of the TF model are varied throughout two different scenarios.

**Keywords:** Voltage Stability Margin, Transfer Function, Smart Grids, Observability Analysis

### 1. INTRODUCTION

Nowadays, a power system must be operated through a reliable and secure scheme in different operating points. Achieving to this aim, one of the prominent factors is an evaluation of voltage stability margin (VSM) in a continuous manner. In this way, it is possible to know how far the power system can move away from its current operating point and still remain secure. For the voltage stability estimation, it is necessary to make the system observable of which a set of measurement data could be available. Indeed, lack of measurement data causes the voltage stability estimation may become impossible. So, an observability analysis must be done before the voltage stability monitoring [1-2].

Observability analysis is a very important tool in state estimation. For a given set of measurements and their location throughout the power system, the observability analysis determines whether the state of the system can be estimated or not [3]. Therefore, an appropriate placement plan for metering devices, by which the observability criteria could be satisfied, is required. Prior to the voltage stability analysis, the distribution state estimation must be performed. The success of voltage stability estimation depends on the number, type, and location of established meters and remote terminal units (RTUs) in the power system [4].

In this paper, an observability based voltage stability monitoring approach is proposed using transfer function (TF) application. In this work, by using the observability analysis and state estimation principle, an optimal placement of metering devices is applied to find the number and location of metering equipment. Then, an online VSM monitoring is proposed by using the TF model. In fact, through the proposed strategy, a relation between planning and operation of

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the power system could be indicated. Moreover, by the proposed strategy, a trade-off between investment cost and real time monitoring capability is obtained.

The proposed VSM monitoring scheme is really compatible to apply to the smart grid pilot project of which it is in the planning phase of progress. In this paper, a practical system case study called Hormoz distribution network is considered regarding to the voltage stability assessment. The Hormoz distribution network is a smart grid pilot project in Iran, in which smart grid issues will be implemented in a chronological road map.

In the rest of the organization of the paper: Section 2 explains the formulation of observability analysis and metering placement. Section 3 suggests the observability based VSM monitoring according to the TF model. In section 4, the proposed approach is applied to the Hormoz distribution network and obtained results are compared in two different scenarios.

## 2. PRINCIPLE OF THE OBSERVABILITY ANALYSIS

As previously stated, the proposed strategy for online monitoring of the VSM has two different parts: one is planning section and another is operating section. In this section, an optimal metering placement based on the observability analysis will be described briefly.

In accordance with observability analysis, an optimum cost selection of metering devices, by which the system remains observable, could be described as follows:

$$\text{Min}(C = \sum_i w_i \times x_i) \quad (1)$$

Where  $x_i$  is a binary decision variable vector. Also, elements of the  $x_i$  could be 1 if a meter is installed at bus- $i$ . Otherwise, the element of the  $x_i$  could be equal to 0. The  $w_i$  is the cost of established meter including the RTU. Indeed, using the above cost function, the network observability could be obtained, while the total installation cost has been minimized. Moreover, the equation (1) is subject to set of rules related to estimation equations. In fact, an optimal answer is acceptable, when the column rank of the Jacobian matrix is full. It could be obtained if the number of linearly independent measurements is equal to or more than the number of state variables. Therefore, only a result could be applicable if it satisfies the estate estimation principle. Between state variables and measurements, a relation could be defined as follows [5]:

$$z = h(x) + v \quad (2)$$

Where  $v$  is the vector of measurement errors. Also,  $z$  is the measurement vector  $m \times 1$ ,  $h(x)$  is a nonlinear function, by which state variables vector of the system is mapped to the measurement vector, and the  $x$  is the state vector  $(2n-1) \times 1$  with  $n$  number of nodes in the system. The state estimation tries to find a state of the system by solving the following equation [5]:

$$\min J(x) = \sum_{i=1}^m w_i (z_i - h_i(x))^2 = [z_i - h_i(x)]^T W [z_i - h_i(x)] \quad (3)$$

Where,  $w_i$  represents a weight factor associated with measurement  $z_i$  and  $r = z - h(x)$ . The optimal solution gives the estimated state  $\hat{x}$  which must satisfy the following optimality condition [5]:

$$H^T(\hat{X})W[z - h(\hat{x})] = 0 \quad \Rightarrow \quad \frac{\partial J(x)}{\partial x} = 0 \quad \text{and} \quad H(x) = \frac{\partial h(x)}{\partial x} \quad (4)$$

Where  $H(x)$  is the Jacobian matrix of the measurement function  $h(x)$ . So, through the proposed metering placement strategy, based on the equation (1), a state vector of the system could be found, by which the  $H(x)$  matrix is full rank. According to the above mentioned, the proposed formulation for metering placement to make the network observable could be formulated as following:

$$\text{Min}(C = \sum_i w_i \times x_i) \quad \text{Subject to the } H \text{ matrix be column full rank} \quad (5)$$

It is obvious that the defined problem is a highly nonlinear problem of which the mathematical approaches could not solve it. In this paper, particle swarm optimization is used to find the global optimum locations [6].

### 3. FORMULATION OF THE VSM MONITORING APPROACH USING TRANSFER FUNCTION MODEL

In this paper, an estimation approach is used to calculate and evaluate the VSM. In the proposed approach, a number of random cases are created, including generator voltage, generator active power, load active power, and load reactive power. Then, according to obtained values in each scenario, the active and reactive flow of branches, the voltage magnitudes and phase angles of buses could be calculated by power flow analysis. Finally, using continuous power flow (CPF), the VSM index could be obtained.

In this paper, a forecasting model based on transfer function (TF) method can be defined. This model is an effective model to anticipate different parameters which is used in different applications. For further evaluation, two different input data combinations for implementation of the TF model are considered:

- Voltage magnitudes and phase angles
- Net active and reactive power injections

In this way, it could be found out what input data combination is well-suited to monitor the VSM. Also, in the proposed method, the input data of the TF model can be sent by metering devices (MDs) which are connected to the system based on observability analysis. Throughout two predefined scenarios, the output of the TF model is the VSM index. It is worth to say that all of following calculations could be performed in an offline state.

Firstly, to estimate the VSM index, it is necessary to create a number of cases randomly. In this paper, a new numerical method is used to generate random input data cases for the power flow analysis. In this approach, a distinct variation factor for load active power, load reactive power, generator active power, and generator voltage magnitude is considered called maximum fractional factor ( $\Delta$ ). This parameter is set to  $\pm 30$  percent of a base value. In the other hand, based on a  $\Delta$  parameter, random cases could be generated. The random case generating scheme can define as follows:

- a) A continuous interval of  $(-\Delta, +\Delta)$  is considered. The purpose is the selection of a random number within the defined range. To achieve this goal, a discrete probability density function is created for each random case, according to equation (6).

$$P_i = \frac{e^{-X_i^{Base}}}{\sum_j e^{-X_j^{Base}}} \quad (6)$$

Where

$P_i$  : A probable value within the (0,1) range.

$i$  : The number of variables in a random case

$j$  : The number of buses in accordance with the type of variables

$X_i^{Base}$  : The base value of the variable- $i$

So,  $n$  probable values can be created using the equation (6) of which  $n$  is the number of related buses depending on the type of variable. It means if the variable is related to generator buses, the number of generator buses must be considered in the formulation. Similarly, if the variable is related to load buses, the number of load buses must be considered.

b) Generate a random number within the (0, 1) range called  $r$ .

c) Calculate a set of  $C_i$  values based on equation (7).

$$C_i = \sum_{k=1}^i P_k \quad (7)$$

d) Find the smallest  $i$  where  $r \leq C_i$ .

e) Calculate a number using following equation in addition to another random number created ( $\bar{r}$ ):

$$A = P_{i-1} + (P_i - P_{i-1}) \times \bar{r} \quad (8)$$

f) Using  $r$  and  $A$ , a random number is selected within the  $(-\Delta, +\Delta)$  interval as follows:

$$D = (2 \times F - 1) \times \Delta \times A \quad , \quad F = \begin{cases} 1 & \text{if } r < 0.5 \\ 0 & \text{if } r \geq 0.5 \end{cases} \quad (9)$$

g) Finally, the value of a related variable for a new random case is:

$$X_i = D \times X_i^{Base} \quad (10)$$

Where  $X$  is one of the electrical parameters used for the power flow analysis, such as load active power, load reactive power, generator active power, and generator voltage magnitude. Using above formulations, the random cases are created. The random generated cases is used throughout the TF model to monitor the VSM correctly.

According to the principle of the TF model, there is a relation between the VSM index and the voltage of buses as follows:

$$VSM(|V^*|, \angle V^*) = \alpha + \nabla(M) \times |V^*| + \nabla \nabla(M) \times (\angle V^*) + \beta(|V^*|, \angle V^*) \quad (11)$$

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Where

$\alpha$  : Constant coefficient

$|V^*|$ : Voltage amplitude

$\angle V^*$ : Voltage phase angle

$VSM(|V^*|, \angle V^*)$ : The VSM index

$\nabla(M), \nabla\nabla(M)$ : Polynomial functions of the back-shift operator

$\beta(|V^*|, \angle V^*)$ : Disturbance term

Also, polynomial functions of the back-shift operator  $M$ , and  $\nabla\nabla(M)$  could be defined as follows:

$$\nabla(M) = \sum_k \nabla_k M^k \quad \text{and} \quad \nabla\nabla(M) = \sum_k \nabla\nabla_k M^k \quad (12)$$

Where

$$M^k |V^s| = V^{s-k} \quad \text{and} \quad M^k \angle V^s = \angle V^{s-k} \quad (13)$$

Furthermore,  $\nabla_k$  and  $\nabla\nabla_k$  are polynomial coefficients which should be selected and estimated to achieve white noise errors. Also, the disturbance factor can be defined as follows:

$$\beta(|V^*|, \angle V^*) = \frac{\hat{h}(M)}{\hat{\lambda}(M)} \varepsilon(|V^*|, \angle V^*) \quad (14)$$

Where  $\hat{h}(M)$  and  $\hat{\lambda}(M)$  have already defined polynomial functions of the back-shift operator and  $\varepsilon(|V^*|, \angle V^*)$  is the error term that is assumed to be a white noise.

$$\hat{\lambda}(M) VSM(|V^*|, \angle V^*) = a + \hat{h}(M) \times \varepsilon(|V^*|, \angle V^*) \quad (15)$$

Where  $a$  is a constant coefficient. Also,  $\hat{\lambda}_k$  are polynomial coefficients defined as follows:

$$\hat{\lambda}(M) = 1 - \sum_k \hat{\lambda}_k M^k \quad (16)$$

Similarly,  $\hat{h}_k$  are polynomial coefficients which could be calculated as follows:

$$\hat{h}(M) = 1 - \sum_k \hat{h}_k M^k \quad (17)$$

It is worth to say that  $k$  is equal to the number of random generated cases. It is important to point out that the formulation of the VSM estimation using the active and reactive power combination as an input data is similar to above equations.

#### 4. CASE STUDY

To assess the proposed VSM estimation method, the metering placement must be done based on observability analysis. In this paper, a pilot project is used to simulate the proposed strategy. The Hormoz distribution grid is a practical system case study of which it is in the planning phase of construction in a smart grid plan. The single diagram of the Hormoz distribution grid is shown in Figure. 1.

Also, the active power and reactive power of loads are shown in Table. 1. The line data also is shown in Table. 2. So, the proposed metering placement is applied to the Hormoz distribution system to find the best location of the metering infrastructures. In this way, using related formulations, the PSO method is employed to minimize the objective function based on observability analysis.

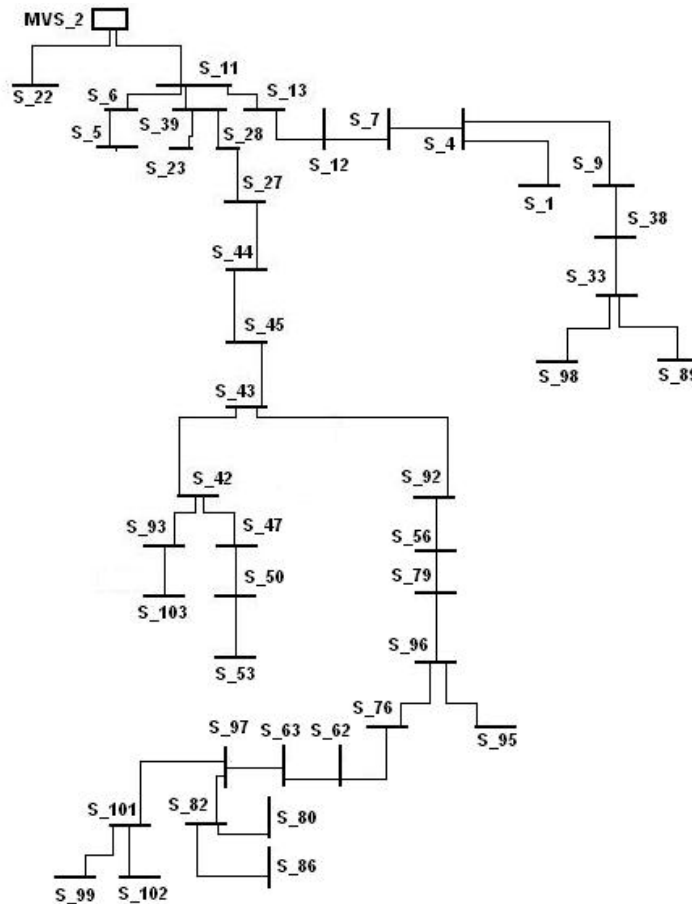
The proposed state estimation strategy is applied to the Hormoz distribution grid in order to make the grid observable. In fact, the metering placement focuses on the power system planning issue. The best place of metering devices is shown in Table. 3. The results are obtained during 10 iterations of the PSO method. The convergence of the PSO algorithm in the optimization process is shown in Figure. 2.

By the metering device installed at specific locations, the Hormoz distribution network could be observable during the operation. In this way, the column rank of the Jacobian matrix of the Hormoz distribution network is full. Also, to make the grid observable, a minimum cost of investment is needed. In the other hand, it is needed to install metering devices only at specific buses instead of all buses in the system.

**Table. 1.** Load active power and reactive power data for the Hormoz distribution grid

Substation	Active Power (kW)	Reactive power (kVar)	Substation	Active Power (kW)	Reactive power (kVar)	Substation	Active Power (kW)	Reactive power (kVar)
S_1	435.4485	90.5511	S_38	593.7355	123.7654	S_80	329.8145	68.5588
S_4	373.5092	77.7698	S_39	445.7095	92.6643	S_82	72.2314	14.9967
S_5	214.6298	44.7345	S_42	325.2644	67.6215	S_86	210.5283	43.8824
S_6	381.673	79.457	S_43	218.199	45.4758	S_89	311.3752	64.7585
S_7	751.9067	156.7837	S_44	215.8604	44.9901	S_92	447.3651	93.0051
S_9	185.0045	38.5739	S_45	363.1179	75.4096	S_93	53.5413	11.0771
S_11	571.2261	118.8659	S_47	130.8008	27.2667	S_95	146.7341	30.4621
S_12	610.2002	127.1738	S_50	31.3068	6.3906	S_96	215.637	44.7345
S_13	559.864	116.5227	S_53	204.7064	42.6724	S_97	149.9217	31.1182
S_22	352.7537	73.2794	S_56	186.9693	38.9829	S_98	550.5716	114.6055
S_23	252.5866	52.6078	S_62	164.7595	34.3561	S_99	55.603	11.5032
S_27	204.3785	42.6043	S_63	258.271	54.0819	S_101	103.1014	21.4044
S_28	277.9918	57.8651	S_76	248.5146	51.7642	S_102	411.5148	85.6175
S_33	365.1917	75.8356	S_79	711.2355	148.0499	S_103	133.4775	27.8121

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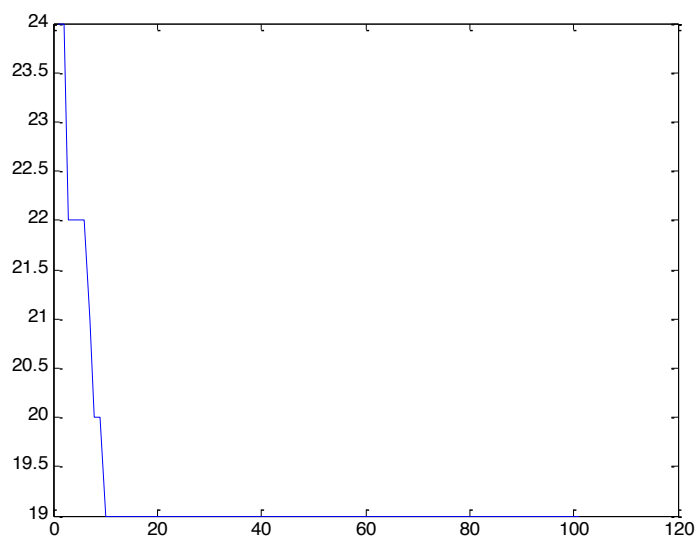
**Figure 1.** Single Diagram of the Hormoz distribution network.

**Table 2.** Lines data for the Hormoz distribution system.

Bus Number	Bus Number	R(Ohm)	Reactance (Ohm)	Capacitor ( $\mu$ F)	Bus Number	Bus Number	R (Ohm)	Reactance (Ohm)	Capacitor ( $\mu$ F)
S_22	MVS_2	0.04	0.0223	0.0014	S_42	S_43	0.1506	0.0805	0.0031
S_11	MVS_2	0.0425	0.0427	0.0034	S_92	S_43	0.041	0.0303	0.0082
S_6	S_11	0.1005	0.0536	0.0146	S_93	S_42	0.1512	0.0807	0.0025
S_5	S_6	0.0767	0.0409	0.0615	S_103	S_93	1.7921	0.9567	0.0006
S_39	S_11	0.0532	0.0537	0.0012	S_47	S_42	0.0761	0.0406	0.0069
S_13	S_11	0.0433	0.0436	0.0014	S_50	S_47	0.1507	0.0656	0.0885
S_12	S_13	0.0138	0.0074	0.0027	S_53	S_50	0.0698	0.0304	0.0012
S_7	S_12	0.0738	0.0394	0.0015	S_56	S_92	0.0332	0.0245	0.0108
S_4	S_7	0.0619	0.0355	0.0083	S_79	S_56	0.0299	0.0214	0.0039
S_1	S_4	0.0968	0.0556	0.0037	S_96	S_79	0.0332	0.0213	0.035
S_9	S_4	0.043	0.0254	0.0019	S_76	S_96	0.2163	0.1387	0.0062
S_38	S_9	0.0825	0.0446	0.0024	S_95	S_96	0.0813	0.0354	0.003
S_33	S_38	0.114	0.0696	0.0015	S_62	S_76	0.0294	0.0189	0.0016
S_98	S_33	0.1043	0.0454	0.0005	S_63	S_62	0.0755	0.0484	0.0798
S_89	S_33	0.0516	0.0225	0.0016	S_97	S_63	0.1644	0.0878	0.014
S_28	S_39	0.0181	0.0182	0.0385	S_82	S_97	0.1677	0.073	0.0026
S_23	S_39	0.1198	0.0724	0.0022	S_101	S_97	0.0845	0.0451	0.0109
S_27	S_28	0.0116	0.0116	0.003	S_86	S_82	0.1098	0.0478	0.0011
S_44	S_27	0.0193	0.0194	0.0038	S_80	S_82	0.0421	0.0183	0.006
S_45	S_44	0.004	0.0059	0.0084	S_102	S_101	2.1406	1.1429	0.0041
S_43	S_45	0.0176	0.0177	0.0074	S_99	S_101	0.104	0.0452	0.0062

**Table 3.** Best places of the metering device installation in the Hormoz distribution network

Method	Bus Number
Particle Swarm Optimization (PSO)	MVS-2, S_5, S_39, S_12, S_4, S_33, S_44, S_45, S_93, S_103, S_50, S_53, S_56, S_96, S_95, S_63, S_101, S_102, S_82

**Figure 2.** The convergence of the PSO method to find a global optimum point for the metering installation

Also, Fig. 2 demonstrates a powerful performance of the PSO algorithm to find the best location of metering devices in an acceptable simulation time around 15 iterations.

The second part of the simulation section is related to operating aspects of the power system. Now, it is desired to analyze the VSM monitoring possibility in the Hormoz distribution network, when the measurement data is reduced. In this part, it is assumed that there are metering devices only at buses mentioned in the Table. 3. Moreover, to find the best input data for the TF model, two different scenarios are considered. In this study, normalized mean square error (NMSE) is used as a performance measure to compare two different input data combinations: one is a reduced input data, and another is the case in which metering devices are connected to each bus. Table. 4 compares the time of estimation through different input data combinations and their NMSE value.

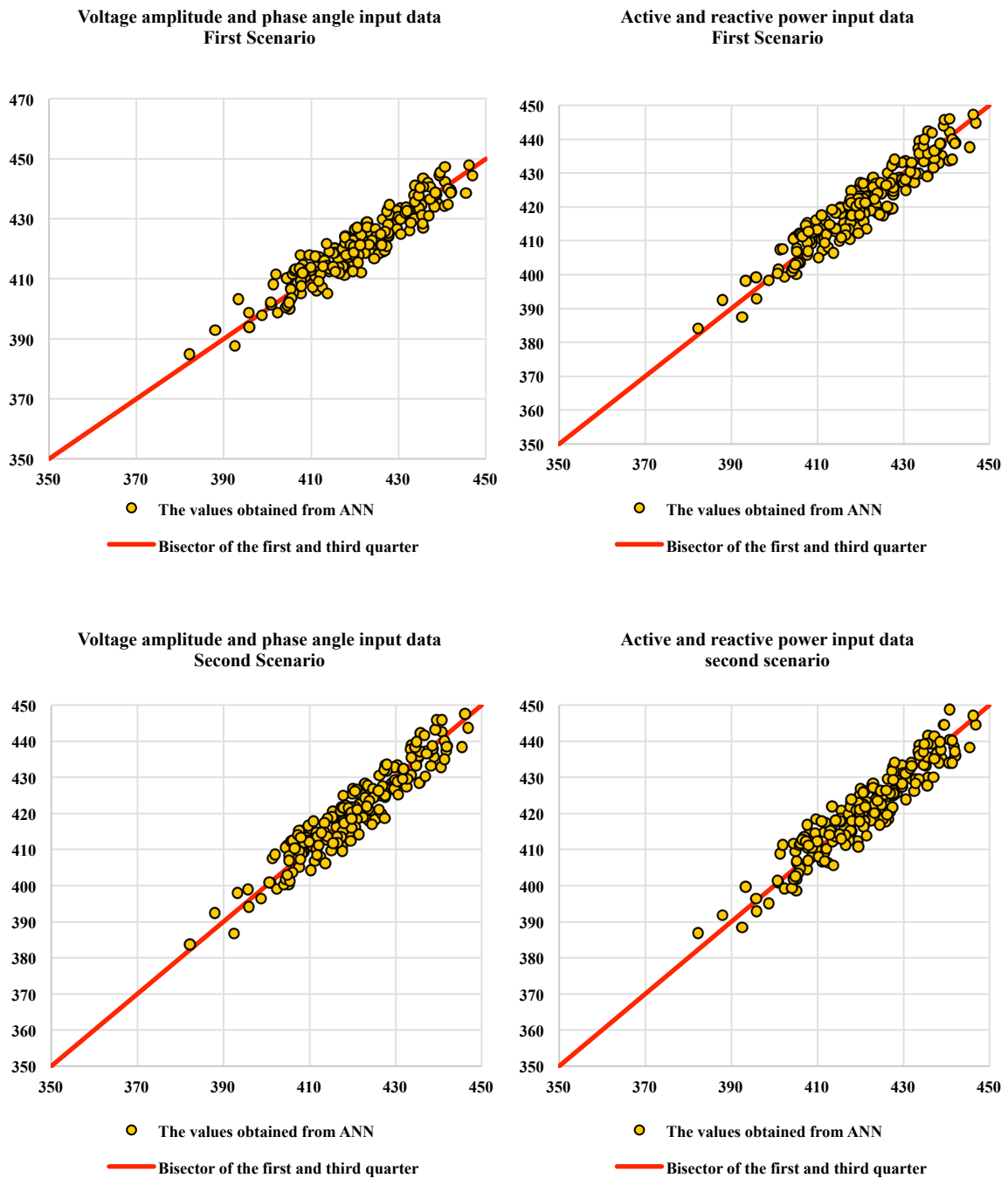
**Table 4.** The comparison of two different scenarios regarding to the VSM monitoring throughout the Hormoz distribution grid.

Scenario	Input data vector	NMSE	Computation Time
Metering devices connected to the buses which are calculated by the observability analysis	Magnitude and angle	$4.2584 \times 10^{-8}$	0.031122
	Active and reactive power	$5.1558 \times 10^{-8}$	0.029562
Metering devices are connected to the whole of buses	Magnitude and angle	$2.5127 \times 10^{-8}$	0.04543
	Active and reactive power	$3.7412 \times 10^{-8}$	0.05532

By comparing the results, one can find out that the active power and reactive power input data combination is better to use for the VSM estimation. In the P-Q combination input data, the time of processing is less than V- $\theta$  input data combination. This feature is crucial during the VSM estimating approach, because it is related to system operating section. By comparing the results, one can find out the proposed method has a similar performance for the VSM monitoring in addition to being cost-effective approach. Furthermore, in our approach there is less data communication between distribution management system (DMS) and smart metering devices. Also, the TF model is a convenient model to monitor the VSM with less input data.

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Figure. 3 illustrates the P margin estimation of the Hormoz power system considering (a) the P-Q data combination (b) the voltage magnitude and angle as an input vector of the TF model obtained in two predefined scenarios.



**Figure 3.** The comparison of the performance of various scenarios: The first scenario is related to a case in which metering devices are connected to specific buses. The second scenario is related to a case in which metering devices are connected to the whole of buses.

## 5. CONCLUSION

This paper presents a novel approach to monitor the VSM index subsequent to the observability analysis in a practical system case study called Hormoz distribution network, Iran. In this way,

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by using the observability analysis and PSO method, an optimal placement of metering devices is done. The results show that it is necessary to install the metering device at 19 buses of the Hormoz distribution grid. Then, the VSM monitoring scheme is proposed using a novel transfer function model. Also, in this work, to create random cases for the TF model, a new numerical method is used. By comparing the results, one can find out the VSM monitoring through the proposed method is quite similar to the case in which all buses have a metering device. So, the proposed method is a more cost-effective way for the pilot project of the smart distribution grid regarding to monitoring capabilities.

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