Configuration of WAMS and Pilot Bus Selection for Secondary Voltage Control in the Egyptian Grid

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***Abstract*— A key feature in smart grids is the ability to provide real time monitoring and control. This paper presents techniques for implementing a Wide Area Measurement System (WAMS) and selecting pilot buses in the Egyptian grid to enable implementing secondary voltage control. The design technique of WAMS includes optimal placement of Phasor Measurement Units (PMUs) and Phasor Data Concentrators (PDCs), as well as their associated Communication Infrastructure (CI), to achieve minimum cost. To generalize the technique, different power grid conditions are taken into consideration such as N-1 contingency analysis (outage of a PMU or transmission line(s) or transformer(s)). Nomination of certain load buses (pilot buses) is the main step to implement optimal secondary voltage control. The method used to select pilot buses considers system-wide information and different operating conditions regarding different load levels and network topologies. The power system analyses were performed using DIgSILENT software while the optimization problems were solved in MATLAB software.**

***Index Terms*—WAMS, PMU, PDC, Pilot Bus Selection, Security Criteria, Egyptian grid, Secondary Voltage Control.**

I. Introduction

The main features of a smart grid are online real-time monitoring, protection, and control in addition to the important property of self-healing [1]. Upgrading a grid to be smart requires cooperative efforts in terms of research, design, implementation, and operation. The requirements and regulations governing power system operation and control are becoming more complex. Therefore, conventional techniques with measurements using a point-to-point supervisory control and data acquisition (SCADA) system may no longer be sufficient for smart grid applications, and the need to use phasor measurement technology to obtain a better estimate of the power system state has increased. As a result, many electrical power utilities are converting from conventional SCADA-based monitoring systems to wide area measurement systems (WAMS) which include phasor measurement units (PMUs) and their accessories [2].

Most of the research papers in this field focus on minimizing the number of PMUs due to high cost; however, all those papers assume that the PMUs are ideal and ignore a PMU's power source, switches, and communication facilities. In this paper, all WAMS components are taken into consideration, and a technique is used to minimize the total cost while keeping high redundancy.

Voltage control in power systems consists of three hierarchical control levels: primary voltage control, secondary voltage control and tertiary voltage control [3], [4]. The primary voltage control aims to control the voltage magnitude of the generator buses, while secondary voltage control aims to control the voltage magnitude of a pilot bus which is a certain load bus influencing voltages at other buses in the system. This control level is normally performed by using hardware that enables adjusting the reference point of the primary voltage control which is located at the same region of the pilot bus at a slower rate than that of the primary level [5].

A key factor for the appropriate functioning of a secondary voltage control scheme is the pilot bus selection [6], [7]. In this paper, the problem of selecting pilot buses of the Egyptian grid was solved considering system-wide information, different operating conditions, and different topologies. The Egyptian grid was simulated based on real utility data and minor assumptions [8]. The simulation was concentrated on the 500 kV and 220 kV levels of the grid, using the DIgSILENT power factory software, as many functions are included in the software including power flow, sensitivity and contingency analyses. The optimal locations of PMUs and the selection of pilot buses were performed on the simulated grid.

The paper is organized as follows: Section II describes the simulation of the Egyptian grid, Section III illustrates the main idea of the secondary voltage control, and Section IV discusses the idea of the WAMS and how to configure it while Section V provides the procedure to select the pilot buses. Section VI presents the simulation results and Section VII summarizes the main conclusions.

II. Egyptian Power Grid

Fig. 1 shows a geo-schematic diagram of the simulated Egyptian grid [9] after being updated to include the added transmission and generation equipment up to the peak demand of 2016 [8]. The simulated grid consists of 23 single-circuit 500 kV transmission lines, 172 double-circuit 220 kV transmission lines, 23 single-circuit 220 kV transmission line, 1 four-circuit 220 kV transmission, 38 (500/220 kV) autotransformers, 213 two-windings unit transformers in addition to loads and static reactive power compensators (reactors and capacitors). In our study, we divided the system into 5 zones: Cairo zone, Alexandria zone, Canal zone, Delta zone and Upper Egypt zone.

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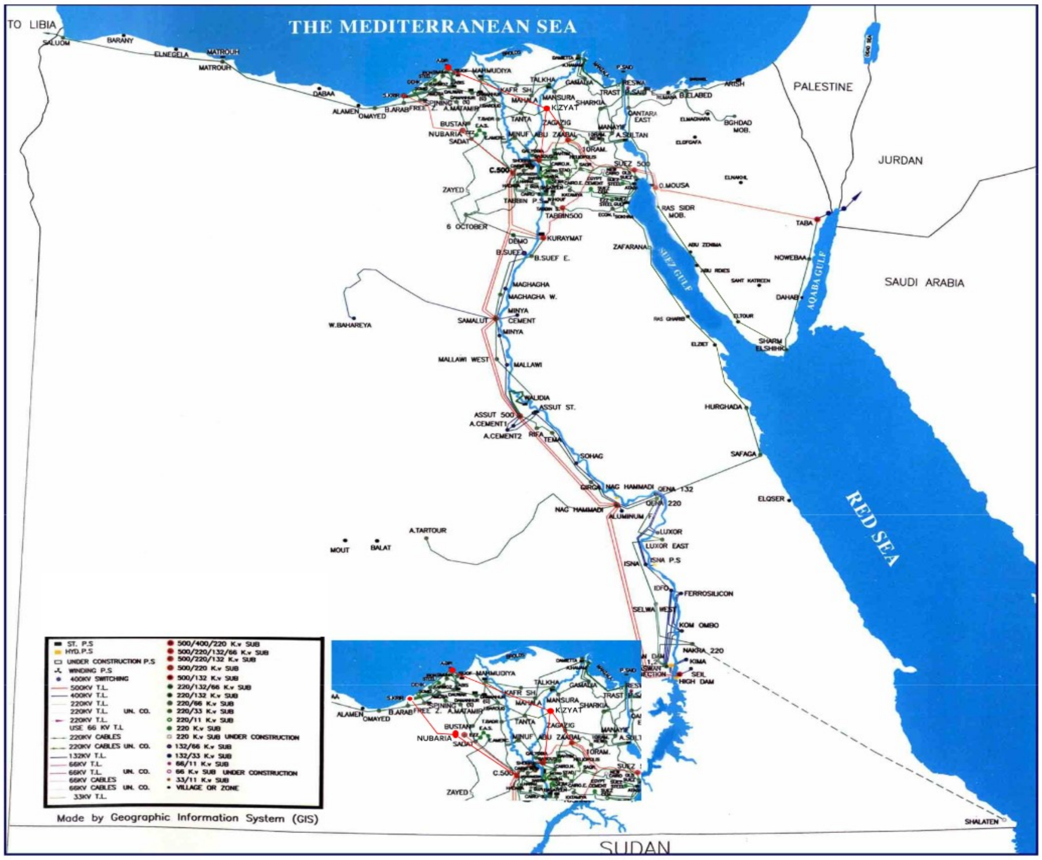

Fig. 1. The simulated Egyptian grid [9]

In order to simulate a real power grid and perform static and dynamic studies, capable software should be used. In this paper, a professional software package called DIgSILENT PowerFactory is used for modelling and system studies of the Egyptian power grid.

Based on the Egyptian grid code, The 500 and 400 kV transmission system shall be planned and operated so that no single contingency, at these voltage levels, results in unacceptable frequency, voltage, or large scale demand disconnection; this known as (N-1) criterion. The 220, 132 and 66 kV transmission system shall be planned and operated so that (N-2) criterion is maintained. These criteria require that the design of WAMS also should consider single PMU outage, single line outage in 500 kV level, or double line outage of 220 kV level.

III. SECONDARY VOLTAGE CONTROL

This paper focuses on preparations to apply secondary voltage control on the Egyptian grid to achieve network stability by performing the control on some selected buses called pilot buses. The appropriate selection of pilot buses would minimize the number of controllers and would maximize the regulation performance when the network is subjected to any disturbance or contingency. The reduction of the number of pilot buses will also facilitate the reduction in complexity of applying the coordination for a large number of controllers.

High and low voltage variations, such as those produced by the hourly evolution of the load, are accounted for by the controllers in the secondary control level; the time constant is in the range of minutes. This level makes use of sub-system information to update the reference values of the controllers in the primary control level with the purpose of keeping voltages of the pilot buses at their optimal values. Through the secondary control level, it is possible to keep an appropriate voltage profile throughout the transmission network in the face of the hourly evolution of the load and topological changes.

The secondary voltage control will be implemented in steps and a linearized model might be used. Three alternatives can be used to describe the relation between changes of voltages and (active and reactive) power variations which are the following:

1. Fast decoupled load flow solution where sensitivity matrix which relates voltage and reactive power variations is made equal to the negative nodal suspectance matrix of the global system.
2. A more detailed model considers the active power flows in the electric network, but neglects the effect of active power changes on voltage magnitudes, and this approach is the base of this research as illustrated in (1).
3. The exact model which considers the effect of incremental variations of active and reactive powers.

$$\begin{bmatrix} S_{GG} & S_{GL} \\ S_{LG} & S_{LL} \end{bmatrix} \begin{bmatrix} \Delta V_G \\ \Delta V_L \end{bmatrix} = \begin{bmatrix} \Delta Q_G \\ \Delta Q_L \end{bmatrix} \quad (1)$$

Where ΔV_G is the change of PV bus voltage, ΔV_L is the change of load bus voltage, ΔQ_G is the change of generated reactive power while ΔQ_L is the change of load reactive power, while S_{GG}, S_{GL}, S_{LG} and S_{LL} are submatrices that represent the relation between a change of voltage with a change of reactive power.

From (1), it is found that ΔV_L can be expressed as follows,

$$\Delta V_L = A\Delta Q_L + B\Delta V_G \tag{2}$$

where A in (2) is the inverse of S_{LL} submatrix while B is a negative multiplication between inverse of S_{LL} submatrix and S_{LG} submatrix.

Since the control should be applied to certain load buses, these are called pilot buses. The control of those pilot buses should maintain the voltage stability and performance in the whole system.

$$\Delta V_P = M\Delta V_L \tag{3}$$

M is a 0-1 matrix with rank ($n_P \times n_L$) to indicate which load buses are pilot buses, n_P is the number of pilot buses while n_L is the number of load buses in the system.

IV. WAMS

The deregulation of the power system has resulted in increased complexity in planning, operation, control, and protection. The SCADA system in power grids should be technically upgraded to achieve optimal operation. As the global trend is to achieve near optimum power system performance, existing SCADA systems may be replaced by WAMS (wide area measurement systems). Time-synchronized and time-aligned phasor data from WAMS allows the following: (i) visibility of dynamics not captured in traditional SCADA measurement systems, (ii) efficient real-time event analysis by precise comparison, like traffic cameras monitoring transmission highways, (iii) visualization of traffic density as well as pattern, (iv) early warnings of trends indicating the beginning of dynamic interactions, (v) improved root-cause analysis of events, and (vi) improved situational awareness. The secondary voltage control requires real data measurements to achieve the following two purposes [10]:

a) Measure the actual instantaneous voltage of the pilot bus.
b) Provide an online estimation of the most convenient allocation of the reactive power requests among the available generating units.

Many power system researchers have used several optimization techniques for the optimal placement of the PMUs. The new contributions of this paper in WAMS are the following:

a) Optimal location of PMUs in the real Egyptian grid.
b) Optimal location of phasor data concentrators (PDCs) in the grid.

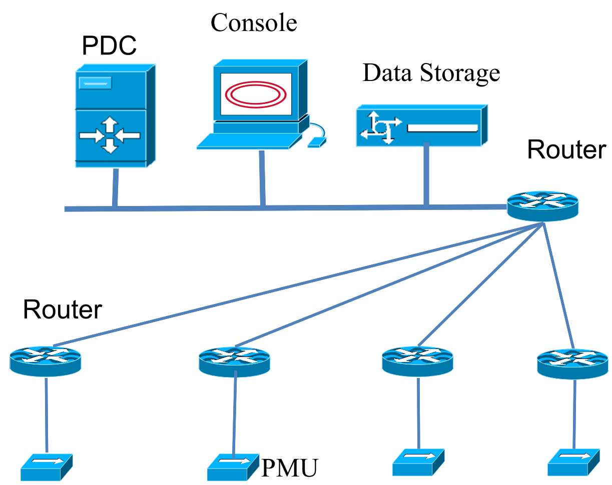

Fig. 2. WAMS Configuration.

c) Optimal locations of (a) and (b) to maintain the grid operational reliability under the N-1 contingency condition (where a contingency here is the outage of a PMU, transformer, or a line).

As shown in Fig. 2, the elements in the WAMS include:

a) PMUs
b) PDC(s)
c) Communication network
d) Operator Console
e) Data storage

As the number of PMUs continues to grow, increased data storage capacity has to be provided. There are thus challenges to apply WAMS in a national grid [11]:

- Problem in some locations due to limitations on cable length of global positioning system (GPS) antenna.
- Unavailability of clearest possible view of the sky.
- GPS sometimes will lose synchronization due to bad weather conditions.
- Non-availability of communication links/channels.
- Non-availability of protection core or restriction of burden on protection core of current transformer.

Fig. 3 shows the flow chart of the proposed algorithm. The algorithm is designed to configure a complete WAMS in the Egyptian grid considering two different sets of operating requirements; however, the realistic challenges in the previous paragraphs may slightly change the optimal placement of a PMU. As illustrated in the Section II, the Egyptian grid is divided into five geographical zones. Next, the optimal PMU allocation in each zone is presented.

A. Optimal PMUs Allocation

The ideal solution would be to install a PMU at each bus bar, but this is not practical because of high costs [10]. Thus, an optimization is formulated as follows:

- Objective function: Minimization of total cost.

$$\min \sum_{i=1}^{n} C_i x_i \tag{4}$$

- Variables: Determine buses to include PMUs.
- Constraints: The power system variables at each bus should be measured by at least one PMU (*K=1*) in the base case or two PMUs in N-1 contingency (*K=2*). The transmission line contingency in the Egyptian grid has N-2 security in the 220 kV level as most of the lines are double circuits so here the algorithm considers N-1 contingency for the PMUs and considers N-2 for the lines achieved in equation (5) when *K=2*.

$$f(X) \geq K \tag{5}$$

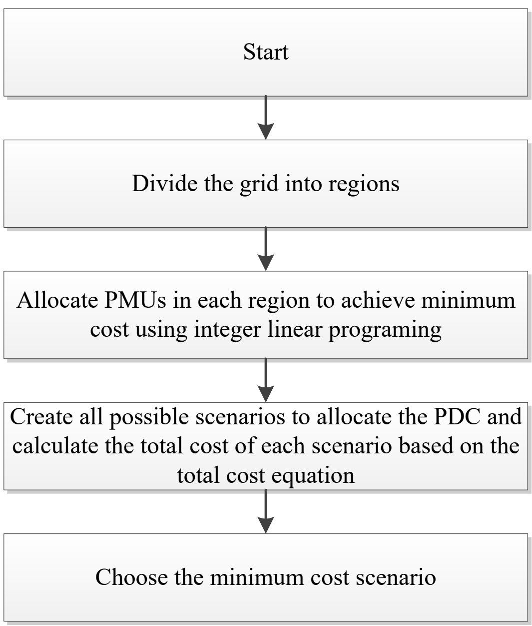

Fig. 3. WAMS optimization flow chart

A PMU can measure the voltage at its own bus and the buses which are directly connected through a transmission line or a transformer to the installed bus. The cost of the PMU includes costs of many components like channels, routers, and communication facilities in addition to the transportation and installation fees. Despite all of these small differences, it can be assumed that all PMUs have approximately the same cost except for the cost of the channels.

B. Optimal PDC Allocation

The motivation for choosing an optimal position for each PDC is to minimize the active and passive costs of the communication network. The cost of the active devices mainly depends on the number of switches and routers installed in system buses to connect the communication links. The cost of the passive devices depends on the lengths of optic fiber medium links. Therefore, by minimizing the cost of these two components, the cost of communication system will be minimized.

The overall objective function can thus be written as follows with the same constraint of (5),

$$min\left\{\sum_{i=1}^{n}(C_i X_i) + C_{fb}\sum_{i=1}^{m}(l_i) + C_{Sw}\sum CI\right\} \tag{6}$$

where C_{fb} is the installation cost for 1 km of optic fiber links and l_i is the total length of the optic fiber links between the i^{th} PMU and the PDC. Also, *m* is the number of PMUs installed in the network, and C_{Sw} is the installation cost of a switch. Every *CI* node is one of the system buses appearing in the communication path from a PMU to the PDC. After allocating the PMUs, we can assume that the PDC is allocated, and the total cost of the communication will be calculated. Finally, the lowest cost indicates the optimal location of the PDC.

In this paper, the optimization process has been performed twice in the Egyptian grid, one for the base case and the other for the (N-1) contingency case. The results are shown in section VII. Only one PDC was chosen for the whole grid.

V. Pilot Bus Selection

The aim of the secondary voltage control is to reach optimal voltages at load buses which are calculated to achieve minimum power loss, minimum cost, or minimum load shedding [12]. This operation will be executed by using the voltage magnitude measured by the PMU, controller, and integrator. Controlled generators will inject reactive power to maintain the voltage at the pilot buses as shown in the following equation:

$$\Delta V_P = AM\Delta Q_L + MB\Delta V_G \tag{7}$$

Pilot bus selection is a highly nonlinear sophisticated problem. No optimum solution model exists to solve such a problem. As shown in Fig. 4, the selection of the pilot buses will be done under different grid conditions. The conditions which are taken into consideration are the base case and the three contingencies which produce the greatest effect on the grid operation. This will result in a set of scenarios; in each scenario, a load flow with sensitivities are calculated. The buses with the highest sensitivity factors are recorded for each region in each scenario. The pilot buses in each region will be selected, recognizing that it is undesirable to transport reactive power over long distances. The intersection between all the scenarios will be considered as the set of optimal regional pilot buses for the grid. To apply this method, four study cases are considered:

a) Case 1: 25% weight factor on base case and 25% weight factor for each of the three contingencies

b) Case 2: 100% weighting factor on contingency number 1

c) Case 3: 100% weighting factor on contingency number 2

d) Case 4: 100% weighting factor on contingency number 3

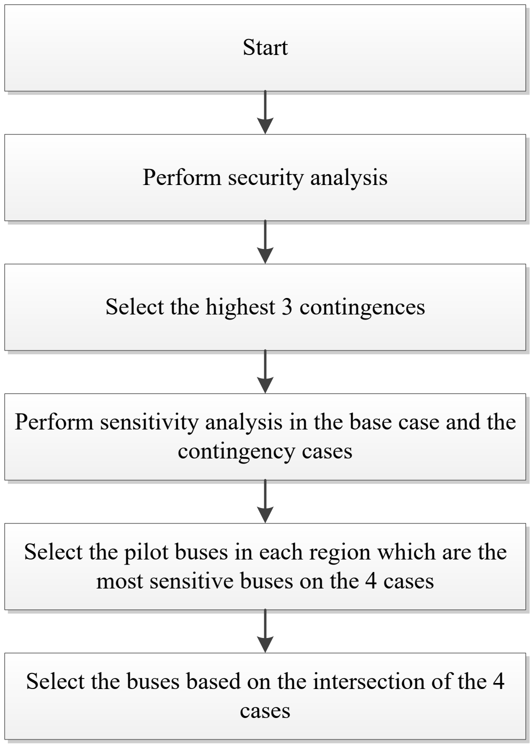

Fig. 4. Pilot buses selection flow chart

After selecting all pilot buses based on the above procedure, we can check the results by performing short circuit analysis. The load buses with highest short circuit currents in each region are defined as the pilot buses because these buses are less sensitive to load changes and then are quite representative of the voltage map [13-15].

VI. Simulation & Optimization Results

A. *WAMS Optimization Results*

Using Matlab 2013a, an optimization for the optimal allocation of PMUs in each region has been performed in two operating conditions, namely; normal condition and (N-1) contingency case. The results are shown in Tables I and II respectively.

TABLE I

PMU allocations in base case

Region	Optimal Buses
Cairo	Heliopolis, Cairo south, Wadi Hauf, Bahtim, Tebeen, Metro Abbasya, Cairo 500, Sheikh Zaid, Shoubra Khema, North October, New Cairo, Tahrir Badr, Cairo 220, Giza, Alshark
Alexandria	AbuKir, Amerya, Saloum, Mantaqa Horra and Sidi Krir.
Upper Zone	Samalut, Fayoum west, Assuit, Gerga, South Qena, Sfaga, Luxor, Salwa, Rabet Khazan, NH 500.
Canal Zone	PortSaeed, Suez 220, Sharkia, Ba2er Abd, Nubaa, Ain Sokhna, Ras Gharib, GabalZeet, Altoor, Shbab, Oyoun Moussa 500.
Delta	Kafr Sheikh, Damnhor, Sadat, Manouf, Kuysina, Kfr Zait, Domiat, Gamalia, Arko steel, Mahmoudia.

TABLE II

PMU allocations in (N-1) contingency case

Region	Optimal Buses
Cairo	Heliopolis, Cairo south, Wadi Hauf, Bahtim, Tebeen, Metro Abbasya, Cairo 500, Sheikh Zaid, Shoubra Khema, North October, New Cairo, Tahrir Badr, Cairo 220, Giza, Alshark
Alexandria	Abukir, Abees, Amerya, Saloum, BorgAlarab, AbuKir 500, M.Matrouh, Ghazl, Mantaqa Horra, Sidi Krir, Sidi Krir 500.
Upper Zone	Samalut, Fayoum west, Assuit, Gerga, Tama, Benisuef, South Qena, Sfaga, Salwa, Rabt Khazan, Khazan, NH 500, HD 500, Samalut 500, Dmo, Walidia.
Canal Zone	PortSaeed, Suez 220, Sharkia, Ba2er Abd, Ain Sokhna, Ras Gharib, GabalZeet, Shbab, Oyoun Moussa 500, Trust, Abukbir, Suez2, Sharm, Nbq, Zaafarana 2, Hurghada, Abo radees, Suez Boot, Proelen, Zagazig, Arish, Oyoun Moussa, Taba.
Delta	Kafr Sheikh, Damnhor, Sadat, Manouf, Kuysina, Kfr Zait, Domiat, Gamalia, Arko steel, Mahmoudia, KfrDwar, Banha, Mansoura, KfrZiat 500, Ashmoon, Sidi Salem, West Domiat, New Domiat, Awlad Hamam, Abukbir, Ezz, MasriaMerkia, Nubaria 220, Mahla, Bostan

In this paper, the average cost of a PMU with auxiliaries is set to be equal to 720,000 LE. The price of 1 km of the fiber optic links as well as the price of one switch is estimated to be 72,000 LE. A complete WAMS configuration simulation was performed on the grid which includes 164 buses. The optimization has been performed as indicated in equation (6), and the results are summarized in Table III. The total cost was calculated in each case by using an Excel sheet and the solver function to obtain the optimal location of the PDC.

TABLE III

WAMS configuration summary of simulation results

Condition	Number of PMUs	PDC location	Number of switches	Total cost
Base case	51	South 220	98	282 million LE
(N-1) case	103	Nubaria 500	160	462 million LE

B. *Pilot Bus Selection*

As illustrated in the previous section, the main idea for the selection of the pilot buses is to calculate the sensitivity at different operating conditions. The cases which have been chosen are the base case and the three highest-ranking (N-2) contingencies, based on the Egyptian grid code. Therefore, a contingency analysis was performed and the results are shown in Table IV. The pilot buses are then selected at the normal condition and then at each contingency as shown in Table V. Finally, from the intersection of the four cases mentioned in the previous section, the pilot buses are determined as shown in Table VI. All calculations have been performed by using the DIgSILENT *PowerFactory* software.

From the results, it can be seen that by using Case 1 which was built by the data of Cases 2, 3 and 4 in addition to the base case, we can determine the optimal pilot buses based on creating different scenarios and taking into consideration different operating conditions. The results agree with the short circuit analysis results as the selected buses also have the highest short circuit current values each in its region.

TABLE IV

Highest ranked contingencies based on N-2 contingency analysis

Contingency rank	Element
1	HD-NH line
2	Zaafarana2 – RasGharib line
3	AinSokhna - Zaafarana line

TABLE V

High sensitivity load buses at different operating conditions

Operation condition	High sensitives load buses	
Base Case	Cairo Region	October, Aboghalleb and Bassous
	Canal Region	Suez-2
	Upper Region	Benisuef
	Delta Region	AlMasria
	Alex Region	Amerya
Contingency rank 1	Cairo Region	Aboghallab, October and Bassous
	Canal Region	Suez-2 and Trust
	Upper Region	Benisuef
	Delta Region	Etay and Mahla
	Alex Region	Dkhila
Contingency rank 2	Cairo Region	Aboghallab, October and Bassous
	Canal Region	Suez-2 and Trust
	Upper Region	Benisuef
	Delta Region	Etay and Masria Merkia
	Alex Region	Amerya
Contingency rank 3	Cairo Region	Kattameya, New Cairo and Metro
	Canal Region	Suez-2 and Trust
	Upper Region	Benisuef
	Delta Region	Etay and Bostan
	Alex Region	Amerya

TABLE VI

Pilot buses selection in each case

Case	Selected pilot buses
1	Etay, Suez 2, October, Aboghallab, Benisuef, and Amerya
2	Same as contingency rank 1
3	Same as contingency rank 2
4	Same as contingency rank 3

VII. CONCLUSIONS

The proposed method for WAMS configuration in the Egyptian power grid has provided a clear technical and financial image of the whole grid in different operating conditions. The optimization procedure for determining the WAMS configuration has also achieved (N-2) security for the 220 kV level and (N-1) security in the 500 kV level as stated in the Egyptian grid code. The configuration of the WAMS based on the contingency case will cost 63% more than the cost of the base case. The simulation of the Egyptian grid by the DIgSILENT software is an important step for pilot bus selection. The proposed method for pilot bus selection ensures proficiency as it is based on different operating conditions, topologies, real geographical divisions, and agreement with the results of short circuit analysis.

VIII. ACKNOWLEDGMENT

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