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Detection & Solution for Out of Step Problem Based on Optimal Location of PMU

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Abstract- Power swing is disturbance done at small part of real grid and case a totally/partial black out of the electrical systems. This paper introduces a real case study for a big power swing event that detected by conventional method of out of step. The relay disconnects the most linewhich has suffered from oscillation but oscillation was moved to rest of power system and did complete black out. A new proposed technique was introduced in this paper to solve the problem of transfer the oscillation to the rest of power network. This technique is based on a developed program usingpower system simulator for engineering (PSSE), power measurement units (PMUs), and artificial intelligence (AI). The technique succeeds to solve the problem without transfer to the rest of the system. The paper also introduced the optimal number and locations of PMUs. in addition, PMUs's are applied to AI system to determine which buses or lines responsible on generate the first oscillation condition.

Keywords- Power swing, total/ partial black out, andthe wide area monitoring - protection and control (WAMPAC) system.

I. INTRODUCTION

Power swing is determined asa variation in three phases active and reactive power flows on transmission lines consequent a large disturbance as faults in the grid [1], [2]. It becomes the reason of generator outage, transmission lines disconnection, false detection & operation of protection devices, and totally/ partial black out of the electrical system. It may be stable/ unstable event [3], [4].

Distance relay & reverse power relay are the most affected devices with power swing case. Distance relay operates as false operation. So, it needs to block method. The conventional blocking methods of distance relay during power swing are appeared as references [5], [6], [7], [8], and [9]. These methods depend on impedance change or the rate of it andused the analog data measuring define as Concentric Characteristic Schemes,Blinder Schemes that may be Dual-Blinder Scheme or Single-Blinder, and Resistance Dot Scheme. The issues of these methods are depending on balanced case and fixed setting.

The other new techniques are used other parameters as:

- Continuous Impedance Calculation as ref. [10], but it depends on the change in the impedance of the transmission lines
- Continuous calculation of incremental current as ref. [11] but it not determines the effect of switching current and fault through high impedance
- Synchro. -phasor Based Out-Of-Step Relaying as ref. [12] that Using compensation units as (series capacitor) with wavelet to detect power swing in but it used high pass filters and that depend on the special device.
- Rate changing in power and Energy as ref. [13], [14] that achieved at time domain in single/ three machine infinite buses.
- Rate of change in relative speed (wr) as ref. [15], [16] depend on change in power with time.
- Swing-Center Voltage and its Rate of Change This scheme is only relevant for a system having only two-sources. There is not a single literature available considering the SVC method applied for large power system network.

(PMUs) make a big revolution in the electrical fields [17]. Depending on integrated relays and using power measurement units in collect data, as References [18], [19], [20], [21], [22]using it with different detection methods. They depend on huge number of PMUs (at list 50% of the station) located in the grid.New researches start to determine the optimal location of PMUs to reduce the number of them [23], [24].

PMUs and AI are used to detect Power swing and determine its location with high accuracy. Reverse power relay used to protect the generator from working at motoring mode [25]. The new algorithm solved that with blocking reverse power relay operation during OOS and control on the input signal to it and sure not false operation and make cascaded generators outage.

In this paper, the optimal location of PMUs is introduced and used with AI to predict/ determine the power swing case then calculate SCV factor in order to determine the zone of power swing and block the risk by out of step relay and control to the signal of reverse power relay to sure not false disconnect of generators.

At the unstable case, determining the rate change of SCV with time

$$\frac{d(SCV1)}{dt}$$

II. OUT OF STEP (OOS) PROTECTION TECHNIQUES

The electromagnetic OOS relay is the old method to detect and work with unstable power swing. Although the fast operation of the electromagnetic relay, it has more parts and terminals need to maintenance and has fixed setting with big size and not recording the events [26].

The new technology of wide area measurements (WAMs) and PMUs can be the new best solution for OOS [27], [28], [29], [30], [31].

(AI) include into the (WAMs) to achieve the control [32] and protection requirements [33] and the wide area measurement protection and control (WAM-PAC) is appeared.

In references [34], [35], [36], [37], [38], [39], [40], and [41] included the (AI) and (PMUs) in detection and operation during OOS.They detect one of the following:

- The rate change of active and Reactive power dP/dt&dQ/dt.
- The continuous measuring of Impedance (ΔZ).
- The rate change of impedance dZ/dt.
- Continuous calculation of incremental current (ΔI).

As reference [42], the rate change in V &Q is used for detection the OOS, but it used as back up protection in the distance relay and define the different with OOS by using the actual value.

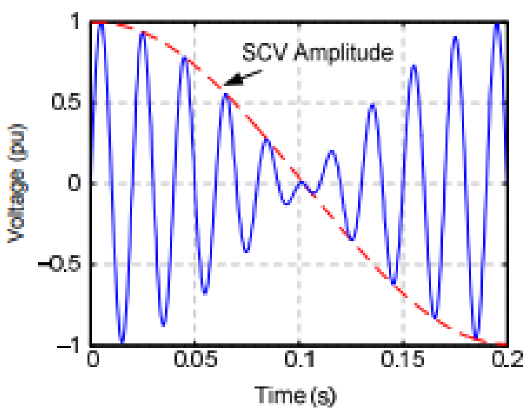

Fig. 1 SCV amplitude during OOS.

As reference [43], SCV methods are defined. It has some advantages as:

- Simple that its values move between (-1 to 1 P.u) and figure 1 show that
- Not depend on the impedance of the transmission lines or the sources
- No need for transient studies.

SCV already has some disadvantages as:

- Take a long time to detect OOS because it depends on the Value of power angle (δ) is 180.
- The voltage drop during heavy load can make it operate before under voltage relay
- It is so bad in define the three phase to ground fault.

All of them in the new method will be faded.

In reference [44], the authors used SCV technique with determine the zero sequence component of voltage in static relay to detect OOS and blocking the distance relay. This technique depended on the analog signal from the current transformer (CT) and voltage transformer (VT) without any modification for the sinusoidal wave. That makes it affected with the conditions of loading and voltage drop.

III. OPTIMAL NUMBER & LOCATION OF PMUS

The function of PMUs is collecting synchronized data from all buses in the power network. All PMUS based on the same global positioning system (GPS) reference time [45]. The economic operation of power system is affect with using the data collected by PMUs.

So, it may not be feasible for a utility to install the large number of required PMUs inall buses and need to determine the optimal number and location of PMUs that achieve the economic conditions [46]. So, PMU must have few number of channels that less than 5 and need rules to choose the most effective parameters that need to transmit them to the control center.

There are a lot of methods used in solve Optimal PMU Placement (OPP) problem. Integral linear programing and binary integer programing and Simulated Annealinggive some simple mathematical equations to do that as references [47], [48], [49], [50], [51], [52].

Also, AI algorithms introduce more developed programing algorithm to achieve that as references [53], [54], [55], [56], [57], [58] but they need more details about the priority of loads and special simulation program with complicated steps.

In reference [59], the authors used more than one method to determine the solution of (OPP) problem for the Iraq

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power network but they didn't make a comparison between result of these methods and Weighting one. In this study, the binaryinteger programingwas implement in The Gene Expression programming (GEP) that is the type of artificial neural network [60].

The rules that used to solve (OPP) problem are:

- For PMU installed at a bus, the bus voltages and the current phasors of all incident branches are known.
- If voltage phasors and current phasors at one end of a branch are known, voltage phasors at the other end of that branch can be obtained using Ohm's law.
- If voltage phasors at both ends of a branch are known, the current phasors through this branch can be calculated

The direct measurement at (a) and indirect measurement at (b & c) are used to get the pseudo-measurement that means calculate the require measurement indirectly by the KCL, KVL, using the correlative measurements.

Simple mathematical array confirmed by the following equation:

∴ The optimal number of PMU

$$(F_i) = \sum_j^n Xj\, Tj$$

Where n: number of branches in the grid, T: the cost of PMU for monitoring the branch, and X is vector dimension j and has binary values defined as:

$$X = |x| = \begin{cases} 1, & for\ PMU\ montoring\ the\ branch \\ 0, & for\ PMU\ notbmontoring\ the\ branch \end{cases}$$

The study network consists of 42 buses and 67 branches and the optimal number of PMU will be 8 at buses (1, 2, 4, 5, 7, 10, 19, and 26). The generator buses have the most priority because they have the important role during unstable power swing case. So, may be the location and number of PMU in the study grid will be changed for another purpose.

IV. REAL CASE OF UNSTABLE POWER SWING

In January 30, 2013; unstable power swing appeared inupper Egyptian network. A Small part from the Egyptian network shown in figure 2 is used at this paper to manage the power transfer on it.

In the above figure; the grid included generator stations as (High bam, koriumat 1, koriumat 2, and walida), extra high voltage branches 500& 220KV, transformer substations 500/220KV connect between the different levels of voltages, load stations include different types of static/dynamic loads, and reactors located in the stations or on the extra high voltage branches 500 KV.

The oscillation voltage& current waves were changed on500 KV transmission lines Samalut/ Cairo &Samalut / koriumat 1 shown in figure 3.

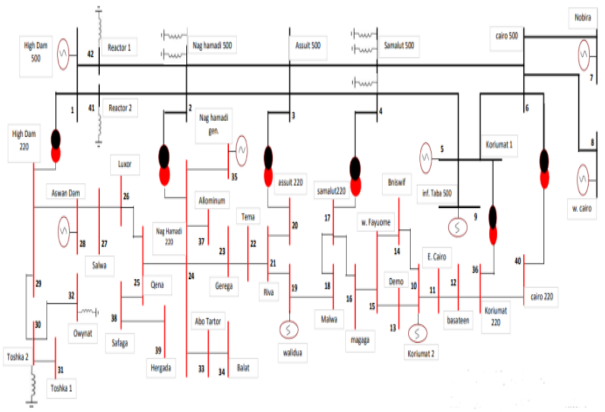

Fig. 2 part of Egyptian grid in Upper Egypt.

During max-peak load condition, the power transfers through the 500 KV lineswasoscillated andcontrol regulators of generators in high dam station sensed. Frequency of oscillation was small value (less than 0.3 Hz) and controlregulators that have smalldead bandof frequency changing, not adaptive to block it and started to grow oscillations not damped and the system become in critical stable mode for 3 min. The other regulators in generator station in network sensed oscillation butblocked them and not do action.

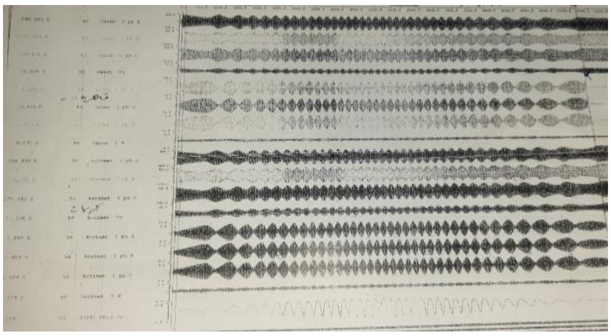

Fig 3. Three phase voltage& current waves of 500 KV transmission lines (1- cairo500/samalut, 2- samalut/ korimat1)

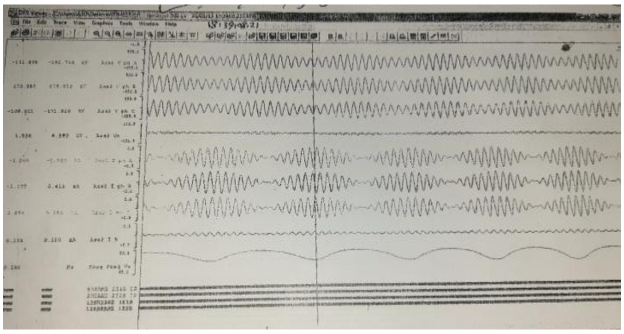

Fig 4. Three phase voltage& current of 500 KV transmission lines (Assuit500/samalut).

All 500 KV lines in Upper Egypt from high dam to Samalut are affected by oscillations swing and figure 4 shown the oscillatory power transfer through 500 KV transmission lineSamalut/ Assyuit500.

Oscillations stay affect on all grid equipment until OOS relay that has c/c(s) in figure 5located in samalut, operated and disconnect 500 KV transmission lines Samalut/ Cairo & Samalut/koriumat 1 when its conditions achieved.

After disconnecting of 500 KV transmission lines in samalut, oscillations not disappeared and lose system its stability limits and become moving to the rest of grid and the components of the grid are disconnected cascaded and the partial blackout of region done.

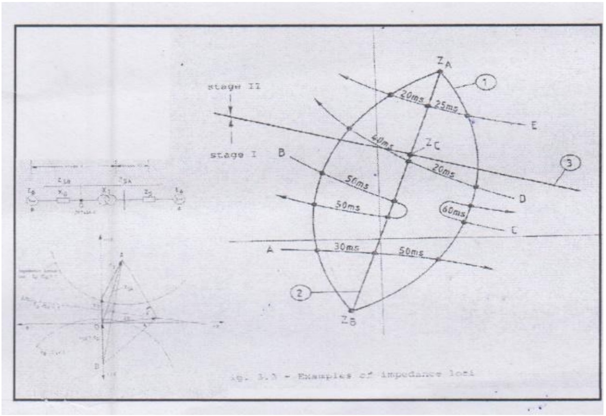

Fig 5. Out of step relay's c/c(s)s located in samalut.

In figure 6, shown the power generation from high dam changed during critical stable mode and the fast outage of units after the out of step relay located in samalut operates. The high dam Insulated with small electrical loads around 400MW even too its loads was 2200MW when the swing power started.

The long transmission lines made high capacitive impedance and the high voltageproblem faced the dispatcher during system restoration.

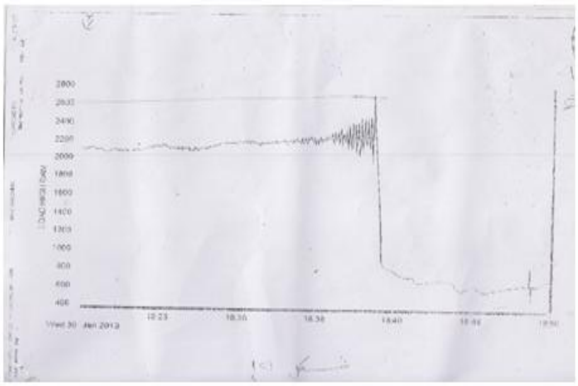

Fig. 6 loading of high dam units before, during, and after power swing case

During this period, the OOS case that madepartial blackoutwas firstly appeared in the upper Egyptian grid and Supervisory Control and Data Acquisition (SCADA) that used in control center didn't collect the fully practical data of OOS case in time. Data wasn't synchronized so the dispatcher engineer in control center couldn't deal with this case manual.

V. PROPOSE TECHNIQUE ALGORITHM

The new technique has the following feathers:

1. Used (PMUs) that put regionally to achieve optimal number in collecting input data for all Parameters from the grid and modified them, thensend to the control unit (CU) and stand to receive the feedback signal and the control order from it.
2. (CU) sends the data to the analyzing (AI) and receive the feedback and action signals according to the calculations.
3. GEP receive data from(CU) and compare it with the storage one in figure 7 and take action from the following:

- If the case sit storage in GEP or not
- If the case is stable OOS, not set in GEP, and don't have any ignore limits, stored it in the memory
- if the case is stable OOS and not sit in GEP, have some ignore limits for any parameter out of the dead band to achieve the prediction of OOS causes, GEP send list of ignore parameters to CU to take the best control action and receive the feedback signal and storage data.
- If the case is unstable or critical stable OOS and sit in the storage memory, the GEP back it to the CU with the best control/protection action in it then get the new data case as feedback.
- If the case is unstable or critical stable OOS and not sit in GEP, GEP send it to the protection unit to check the optimal solution of that case.

4. Protection unit that has algorithmic flow chat in figure 8, receive the unstable or critical case come from GEP and determine the following:

- Buses angles different ($\Delta\delta$) for all buses and determine the two buses increases to be equal 160°
- Check most equipment that affected with OOS case, trip them and sure the OOS not move to the rest grid.
- The best action back to CU and send to PMUs to do it in the grid then the result receives in GEP for future.

The protection unit depends on the following mathematical equations:

From the steady state power equation,

$$\mathbf{P = \frac{Es*Er}{Xs} \sin(\Delta\delta)(1)}$$

The two terminal voltages Es, Er are approximately equal

The electrical power depends on the power factor (ϕ),

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$$P = Es * Il\cos\phi \qquad (2)$$

Where the current in is IL cross in Xs between the two voltages Es&Er defines:

$$IL = \frac{Es - Er}{Xs}$$

In equilibrium condition (1) equal (2):

$$Es * \frac{Es - Er}{Xs}\cos\phi = \frac{Es * Er}{Xs}\sin(\Delta\delta) \quad (3)$$

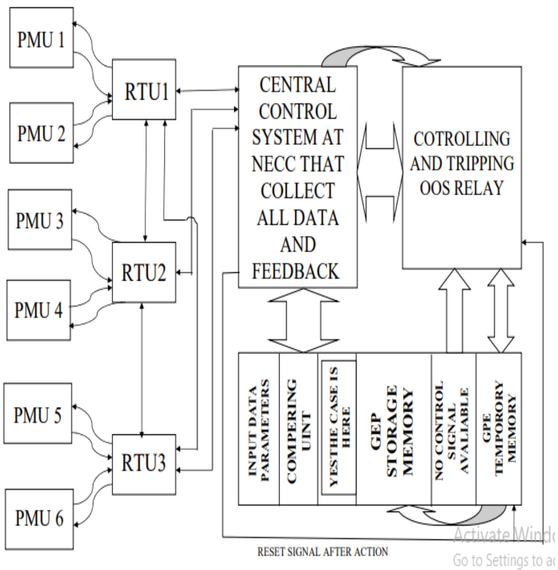

Fig. 7 simulation components of new technique

To determine the relation between δand ϕ using the diagram in fig. (9).

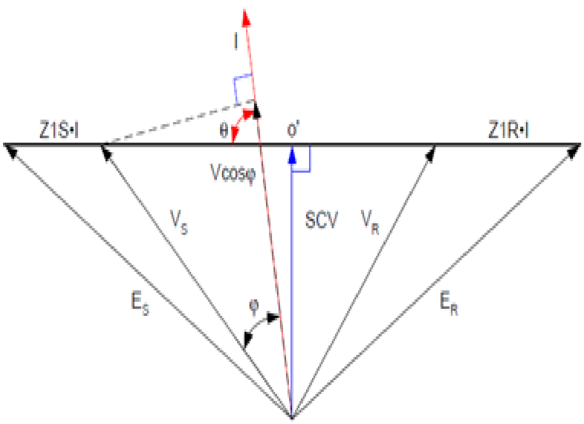

Fig 8. SCV and relation with power angle at voltage diagram and power factor ϕ

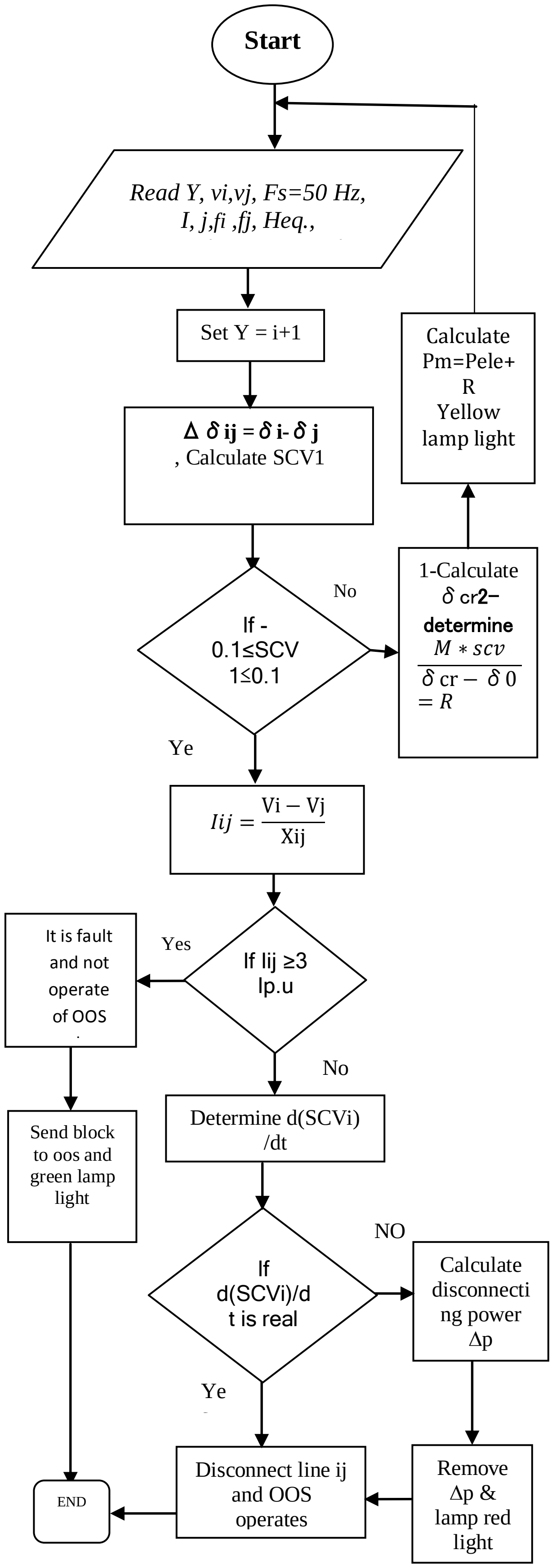

Fig 9. Flow chart of OOS relay.

$$\therefore Es(\cos\delta - \sin\delta) = Er\cos\phi\,(4),$$

And

$$\therefore SCV = Es\cos\frac{\delta}{2} \qquad (5)$$

\Es is the positive magnitude of Vs and δis the difference angles between sending and reserving voltage angles. If δ=180° ⇒**SCV** =0 and the system in unstable in steady state.

From the transient case, equation will be relating to time domain (t).

So, determine the rate of **SCV** with time (t)from the following equation:

$$\therefore \frac{d(SCV1)}{dt} = -\frac{E1}{2}\sin\frac{\delta}{2} * \frac{d\delta}{dt}(6),$$

And

$$\frac{d\delta}{dt} = 2\pi(fi - fs)$$

$$\therefore \frac{d(SCV1)}{dt} = \pi E1 * (fi - fs)\sin\frac{\delta}{2}(7)$$

Where: fi & fs are the two frequencies of the system before and after power swing at steady state at bus affected with OOS**.**

For Suring in sub-transient power swing, the inertia of the generators in the grid has very important role to face Power swing case.so, the equation including the inertia constant (M) factor is more Often used effectively and the digital program can calculateit accurately.

$$¥\frac{d\delta}{dt} = \sqrt{\int_{\delta 0}^{\delta}\frac{2(Pm-Pe)}{M}}\,d\delta(8),$$

$$\frac{d(SCV1)}{dt} = Emax * \sin\frac{\delta}{2} * \sqrt{\int_{\delta 0}^{\delta cr}\frac{(Pm-Pe)}{M}}\,d\delta(9)$$

The calculation of $\frac{d(SCV1)}{dt}$ effect on the decision of the control unit that may choose the correct action that may be changing the flow power (P&Q) or protective action and OOS relay operates.

If $\frac{d(SCV1)}{dt}$ is **real value,** the disturbance will be critical stable power swing around this bus. So, there is a control action can use in damping oscillation before disconnect.

If $\frac{d(SCV1)}{dt}$ is **imaginary value,** the disturbance will be unstable power swing and the OOS relay operate and disconnect the equipment to face unstable power swing.

The algorithm of GPE is a forecast function of abnormal cases, designs to less the time of detection the OOS cases, and used as a large storage memory for them to use it in the future one. It uses the receive data from PMUs in predict them before happen and choose the optimal action control/ protection mode.

Before starting calculations, must determine the critical time (Tcr) and critical angle (δcr)at the bus affected by power swing.

VI. RESULTS AND COMMENTS

This case defines the power swing in the two lines in the real grid samalut / Cairo 500 and samalut / koriumat1 during small time and figure 10 show oscilation where the line koriumat / cairo is disconnect.

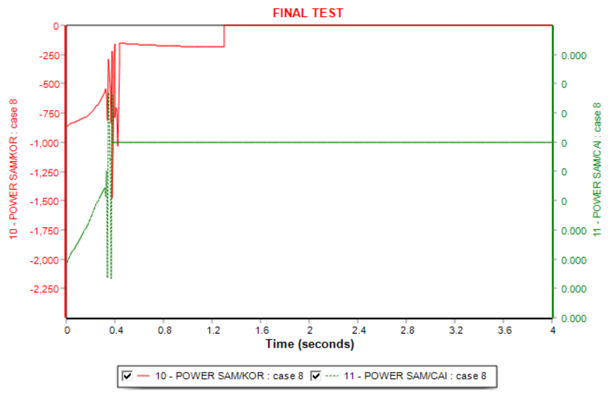

Fig 10. Power transfer into samalut /koriumat&samalut / Cairo500.

The angle of the 3 buses will be in radian get from figure 11, 12, 13

According to figure at (t=0.4) the angles will be:-Samalut angle = 0.25rad,

Cairo angle = 2.55 rad, Koriumat angle = 1.5 rad

To determine the SCV between the buses to show the source of oscillation:

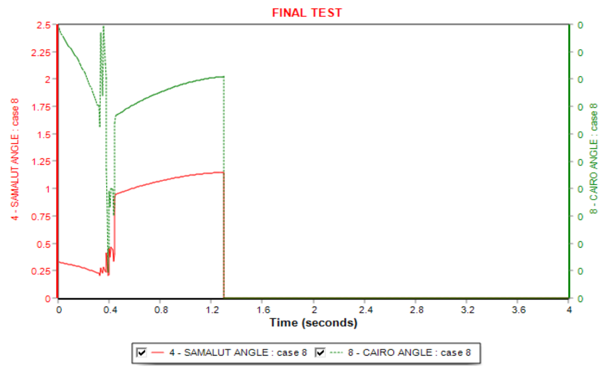

Fig 11. Power angle of buses samalut & Cairo500.

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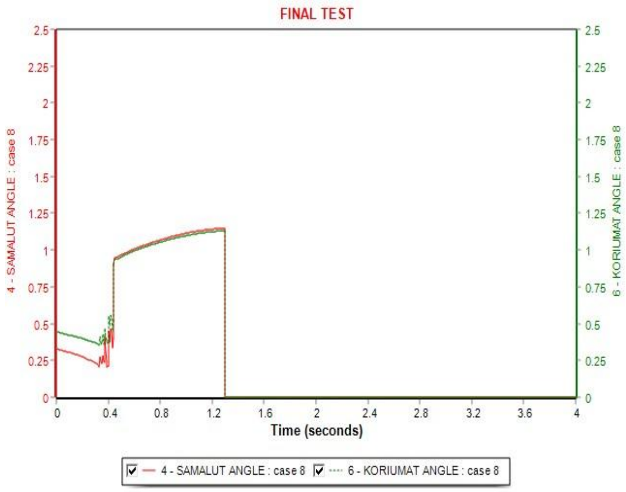

Fig 12. Power angle of buses koriumat1 & samalut.

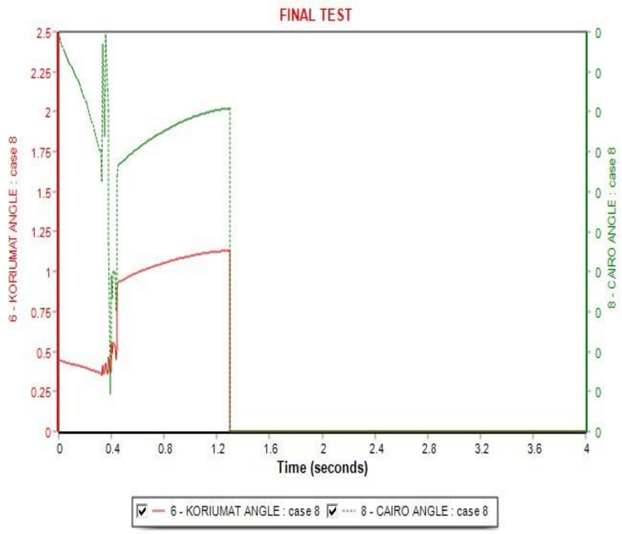

Fig 13. Power angle of buses koriumat1 & Cairo500.

1. For samalut / Cairo line:

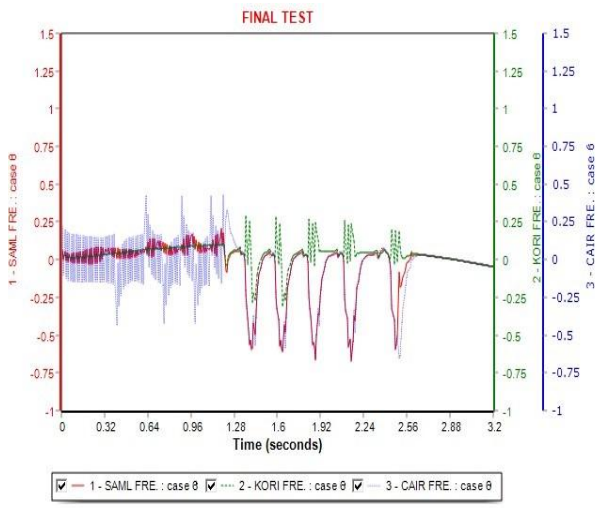

Fig 14. Frequency of buses samalut & koriumat & Cairo500.

$$\therefore \mathbf{SCV}\rfloor_{sam/cairo} = \frac{\cos(\frac{0.3--2.55}{2})}{2} \Rightarrow \mathbf{SCV}\rfloor_{sam/cairo} = \mathbf{0.07Epu.}$$

So; the oscillation grows on this line and need to disconnect but need to calculation the transient conditions according tofrequency figure 14.

According to the figure:

$$\frac{d(SCV1)}{dt}\rfloor sam/car = \pi * (0.05 - 0.2)\sin\frac{(0.25 - -2.5)}{2}$$

So; $\frac{d(SCV1)}{dt}$ is not real values and the relay will operates

2. For samalut / koriumatline:

$$\therefore \mathbf{SCV}\rfloor_{sam/kori} = \frac{\cos(\frac{1.5--0.25}{2})}{2} \Rightarrow \mathbf{SCV}\rfloor_{sam/kori} = \mathbf{0.36E\ pu.}$$

The $SCV\rfloor_{sam/kori} > 0.15$ and the line not need to disconnect by changing the transfer power into this line the oscillation will be damped.

The ΔP is calculated from the initial different angle (δ0) and (δcr) according to the following:

$$\therefore \Delta P = \frac{\frac{d(SCV1)}{dt} * M}{(\delta cr - \delta 0)} \Rightarrow \Delta P = \frac{-0.384 * 10}{(0.7 - 0.25)} = -0.84\ \mathbf{pu}$$

Where M = 10 pu (according to number of generators in the grid)

For improving the transient stability, the system must get the following:

- Minimize fault severity and duration
- Increase the rotating reserve of the system
- Reduction of the torque by: (a) Control of prime mover (b) Application of artificial load

VII. CONCLUSION

Power swing is a very big disurbance that be stable, critical stable, or unstable. The system is shutting down and blackout done becouse of unstable case.

The system risks due to power swing are:

- Transient recovery voltage causing breaker failure
- Isolating load and generation
- Equipment damage.
- Cascading false tripping of transmission lines.

It appeared at apart of Egyptian grid as avery deep and contious disturbance and the reason notaccurately defind and the old method (electro magnatic out of step relay) try to isolated the swing. In this paper, There are many causes that be the power swing conditions and new solution depend on PMUs will be more affect than the old method.

The new technique tries to use the control fasalities as the first defance line before tripping the equiment and not operating of relayExcept when absolutely necessary.

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