Analysis of Grid Disturbances with Modular Load Flow

SUNDARI SRAVAN KUMAR[1]

Professor Department of Electrical & Electronics Engineering, Raajdhani Engineering college, Bhubaneswar, India

***Abstract*— Since the reactive power capacity of the majority of generators are likely expended, iterative load flow (ILF) is not the best method for analysing the conditions just before blackouts. Because of this, choosing PV buses and defining their voltages is challenging. Inadequate voltage specs at the PV buses may prevent ILF from converging. We suggest a non-iterative method called Modular Load Flow (MLF), which does not call for the specification of voltages at PV or slack buses. Non-convergence problems are not present, and the outcome is a single, conclusive answer. A significant outage on July 31 in the Indian Grid is examined.**

Keywords—blackouts, load flow, iterative load flow, ill-conditioned systems, modular load flow

I. INTRODUCTION

The Indian Grid experienced two significant grid disturbances on July 30 and July 31, 2012. Due to these interruptions, nearly half of the country was left in the dark. Traditionally, load flow is used to study disruptions. The iterative load flow process (ILF) has drawbacks when blackouts are imminent. According to conventional load flow, one bus must be designated as a slack bus. When conducting a load flow for the entire grid and its constituent sub-grids, this decision is not entirely evident. Varying outcomes could be attained by selecting different numbers of single or multiple slack buses. This also applies to PV bus voltage standards, whose selection is challenging. Initial conditions must be established using a base case load flow for time domain simulation as well. The findings of the non-converging and non-unique load flow make benchmarking the entire grid problematic.

Most generators in the system are anticipated to exhaust their reactive capacity before blackouts (seventeen generators are reported to have tripped on over-excitation in a major blackout in U.S. [1, pg. 96]). Thus, determining the bus voltage specification needed to conduct a load flow under tough circumstances becomes challenging (Load flow simulations fail to converge without ignoring VAR limits [2, pg. 160]). Results may thus be deceptive. The solution suggested in this research does not require slack or the PV buses to be specified (and therefore voltages). Generators are regarded as consistent power sources when dealing with modular load flow (MLF). Data are taken from the generations in the independently managed regions. These are offered by SCADA. These specs are sufficient to establish all flows, losses, and voltages analytically.

II. MODULAR LOAD FLOW

Loads that are exhausted by a generator's capacity cannot be represented by constant PQs. The system is depicted as a passive network with loads acting as impedances. The conceptual systems on which Modular Load Flow (MLF) is based each have a single connected generator to the passive power network. In this hypothetical system, power injection results in losses in various components, with the load power being the loss in the load component. Power fractions can be used to obtain this distribution [3]. Kirchhoff's rules are embedded in power fractions, therefore no real calculations of voltages or currents are necessary. Only the network's parameters and structure affect power fractions. There are L element power fractions with regard to each connected generator if there are L elements in the network. Thus, we have power fractions of (L x ng). Since power loss is a scalar in each element, all fractional powers from generators can be added together in one element. Contrary to popular assumption, this superposition is true if power sources include generators. Two expressions are used to express power loss in an element in a formal analytical manner. The first of them is described as power entering the element, and the second as power leaving it. The expended power expression can be used to create an expression for power "flow" on a line. The net flow in the transmission line or load elements is calculated as the sum of the power flows contributed by the generator. Reactive power loss in the element is easily accessible after obtaining power loss because, Q/P = X/R in an impedance. The impedance-voltage triangle's newly found Pythagorean property is used to calculate the voltage magnitudes across all elements. Voltages across load impedances are known as load voltages. It should be emphasized that this approach can only be used to measure voltages "across elements." This approach cannot be used to determine node voltages that are not element voltages, such as voltages at other ends of dangling lines without a shunt connection to ground. In power systems, this scenario is improbable because, in theory, shunt charging admittances always exist at every node. There is no voltage reference in MLF since there is no slack bus. The only changes between the two terminal bus voltages of the elements are in the phase-angle. The relevant element-voltage triangles can be used to generate these expressions.

III. ANALYSIS

A. One generator

As the method is not yet widely known, we will briefly reproduce some results from [3]. Consider Fig. 1.

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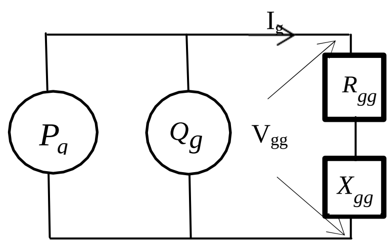

Fig.1. Only one generator feeding the network

$R_{gg} + jX_{gg}$ is the driving point impedance at the generator bus. At generator bus we have,

$$V_{gg} = Z_{gg} I_g \quad (1)$$

$$Z_{gg} = R_{gg} + jX_{gg} \quad (2)$$

Since injected power P_g must equal power consumed, I_g can be written as,

$$I_g = \sqrt{\frac{P_g}{R_{gg}}} \quad (3)$$

Noting the network structure in Fig. 1, (3) implies reactive power of magnitude,

$$Q_g = I_g^2 X_{gg} = \frac{P_g}{R_{gg}} X_{gg} \quad (4)$$

With condition, $Q_g / P_g = X_{gg} / R_{gg}$, we have,

$$I_g^2 = \sqrt{\frac{P_g^2 + Q_g^2}{R_{gg}^2 + X_{gg}^2}} \quad (5)$$

Voltage across a general element is,

$$v_{mn,g} = (Z_{mg} - Z_{ng}) I_g \quad (6)$$

Corresponding current is,

$$i_{mn,g} = y_{mn} v_{mn,g} \quad (7)$$

where, *m* and *n* denote 'from' and 'to' nodes of the element. Complex power in element is given by,

$$s_{mn,g} \equiv p_{mn,g} + jq_{mn,g} = v_{mn,g}\, i^*_{mn,g} \quad (8)$$

$$s_{mn,g} = \frac{P_g}{R_{gg}} \left|\left(Z_{mg} - Z_{ng}\right)\right|^2 y^*_{mn} \quad (9)$$

Real part of 'multiplier' of P_g in (9) is termed as 'power fraction',

$$\varepsilon_{eg} \underline{\otimes} \mathrm{Re}\left\{ \frac{1}{R_{gg}} \left| Z_{mg} - Z_{ng} \right|^2 y^*_{mn} \right\} \quad (10)$$

Equation (9) can be split into two terms in subtractive form as,

$$p_{mn,g} \equiv \mathrm{Re}\left\{ \frac{P_g}{R_{gg}} Z_{mg} \left(Z_{mg} - Z_{ng}\right)^* y^*_{mn} \right\} - \mathrm{Re}\left\{ \frac{P_g}{R_{gg}} Z_{ng} \left(Z_{mg} - Z_{ng}\right)^* y^*_{mn} \right\} \quad (11)$$

In (11) we can see that first term on the right is power flowing 'into' the line *m-n* and the second is that flowing 'out'. With line-loss considered relatively small, the power flow 'on' the line can be written as,

$$p_{mn,g(f)} \equiv \mathrm{Re}\left\{ \frac{P_g}{R_{gg}} Z_{mg} \left(Z_{mg} - Z_{ng}\right)^* y^*_{mn} \right\} (12)$$

From (12) we define *flow fractions* as,

$$\varepsilon_{mn,g(f)} == \mathrm{Re}\left\{ \frac{1}{R_{gg}} [Z_{mg} \left(Z_{mg} - Z_{ng}\right)^* y^*_{mn} \right\} (13)$$

It is to be remembered that all derivations given above are obtained with *only one generator connected to the system.*

B. Loss

When calculations in sub-section A are done for all generators, total loss in element is given by,

$$p_{mn} = sup \sum_g \varepsilon_{mn,g} P_g \quad (14)$$

Similarly, the total real and reactive power *flow* in element *m-n* are,

$$p_{mn,g(f)} = sup \sum_g \varepsilon_{mn,g(f)} P_g \quad (15)$$

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$$q_{mn,g(f)} = \frac{x_{mn}}{r_{mn}} p_{mn,g(f)} \qquad (16)$$

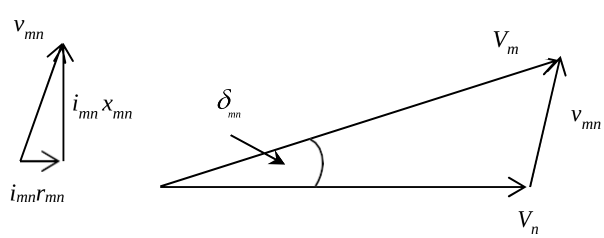
Operation *sup* $\sum_{g}$ in (14)-(15) is 'superposed sum'; some terms may have negative sign depending on direction ofthe power flow.

C. Voltage

Voltage across an element is obtained from the smaller voltage triangle shown in Fig. 2. Note that the discriminant displayed can be written in terms of real and reactive spent powers (15) and (16) in the element as follows.

$$v_{mn} = \sqrt{p_{mn} r_{mn} + q_{mn} x_{mn}} \qquad (17)$$

Bigger triangle in the Figure has sides equal to bus voltages V_m, V_n and the element voltage, v_{mn} (all voltages in pu).



$$v_{mn} = \sqrt{i_{mn}^2 r_{mn}^2 + i_{mn}^2 x_{mn}^2} \qquad \delta_{mn} = \frac{v_{mn}}{V \approx 1} \approx v_{mn}$$

Fig. 2 Voltage triangle for element

It is noted from Fig. 2 that the phase-angle difference (in radians) across the element *m-n* is,

$$\delta_{mn} = \frac{v_{mn}}{V \approx 1} \approx v_{mn} \qquad (18)$$

IV. ASSUMPTIONS AND MODELLING

Fig. 3 depicts the Indian Power Grid separated into five regional grids. On July 31, 2012, a significant blackout affected the NEW grid, which consists of the Northern, Eastern, and Western parts. load of 28053 MW. It has 3 boundary buses numbered 6, 11 and 12. Load assigned to each is thus 9351 MW. Generation of 32612 MW is

region. We employ our method to analyse conditions immediately preceding the blackout.

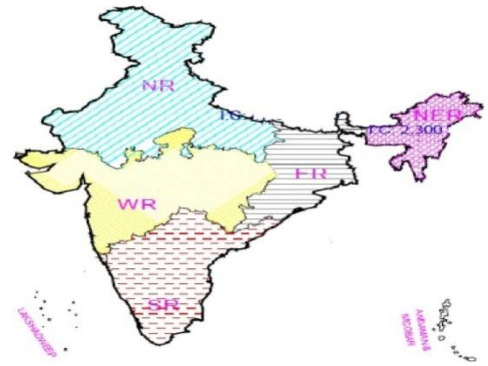


Fig. 3Indian Power Grid

Load Representation

Loads cannot be represented by continuous PQ because it is likely that generators will be working at their capability limits and that they will only be supplying loads with as much power as their generators are capable of supplying. They are going to be represented by constant impedances in MLF. The nonlinear loads represented by constant impedances vary with the square of the voltage. We also suppose that in order to transfer real power to loads, generators must give reactive power, say 30 percent of it. The reactive power component of each load MVA is similarly considered to make up 30% of its active power.. This assumption would give power factor of about 0.95 Generally loads are advised to keep power factor near unity, else they have to pay heavy penalty. Reactive power values are usually available from SCADA in which case no assumptions need to be made.

A. Radial-Mesh Representation for Regional Network

Radial-Mesh (RM) representation tries to capture 'nodal' property of a region in the grid as also the 'distribution' property within the region. We first obtain an RM type network representation for each region from available data of generations and tie line flows from antecedent conditions [4]. The total load of the region is equally distributed among the boundary buses of the region. All generation is assumed to be located at a central bus. For example, WR has total

Line flows, element voltages (load voltages are voltages across load impedances), as also the angle-differences, can be analytically obtained from (15), (17) and (18).

at the radial center bus – the generator bus numbered 1. Transmission line elements exist between each boundary node and the generator bus, and also between a boundary bus and the two adjacent buses (Fig.4).The inter- regional radial lines and those between boundary buses are assigned typical line impedances of 0.001 + *j*0.004 pu on 1000 MVA base. Charging admittances of 0.0001 are added to all lines. Tie line impedances are

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taken to be smaller by a little bit higher, 0.005 pu, assumption is made for an order and their billing admittances. To match the measured line flows with the load flow values, the tie line impedances needed to be adjusted. Each area of the interconnected grid is represented as a radial-mesh system based on the provided antecedent conditions. The Southern area's load is equal to the total electricity flowing from the Western and Eastern regions to the Southern region, and it is asynchronously connected to the Northern grid. The findings of the modular load flow on this model of the NEW grid correspond to the measured power flows on tie lines at 12.30 on July 31. Fig. 5 displays a single line representation of the NEW grid with a newly built network.

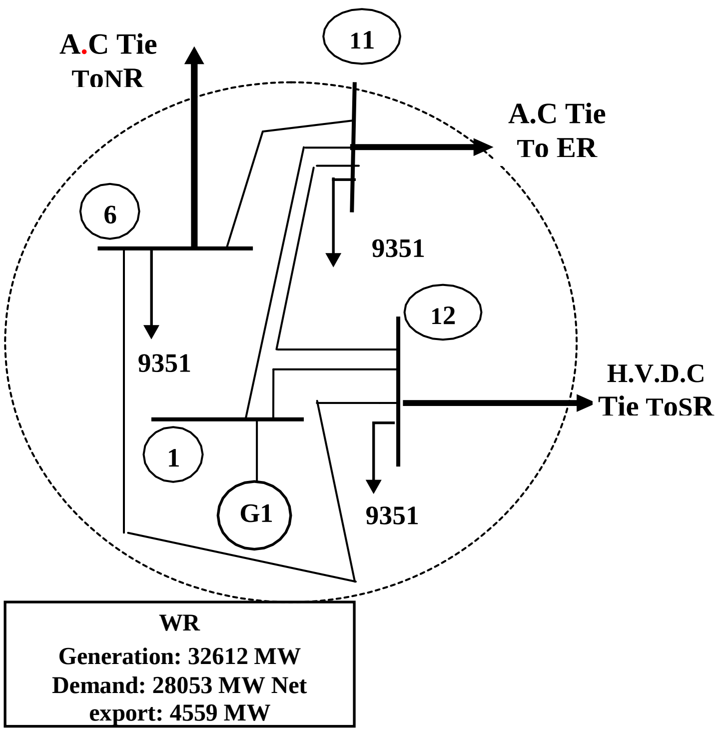

Fig4. Radial-Mesh Network

B. Benchmarking

We run MLF for the NR for conditions on July 31 at 12.30 hrs. for benchmarking. Results are compared to the tie line flows before to the interruption. To accomplish this, a few factors may need to be adjusted. After benchmarking, MLF is used to calculate the relative variance in line flows and bus voltages for incremental changes in loads. Our calibrated model is this. If precise networks for the locations are provided, the procedures above are not essential. It is essential for the system's security to be monitored in the days leading up to the blackout. Understanding the trend is preferable in order to plan ahead and take timely steps to avoid blackouts. The calibrated model was simulated by increasing the load in the NR region starting from the antecedent conditions at 12.30 hrs on July 31, 2012. In order to visualize margins available, usages of tie line capacities were plotted as percentage of their upper limits (Fig. 6). The limits are taken from [7].

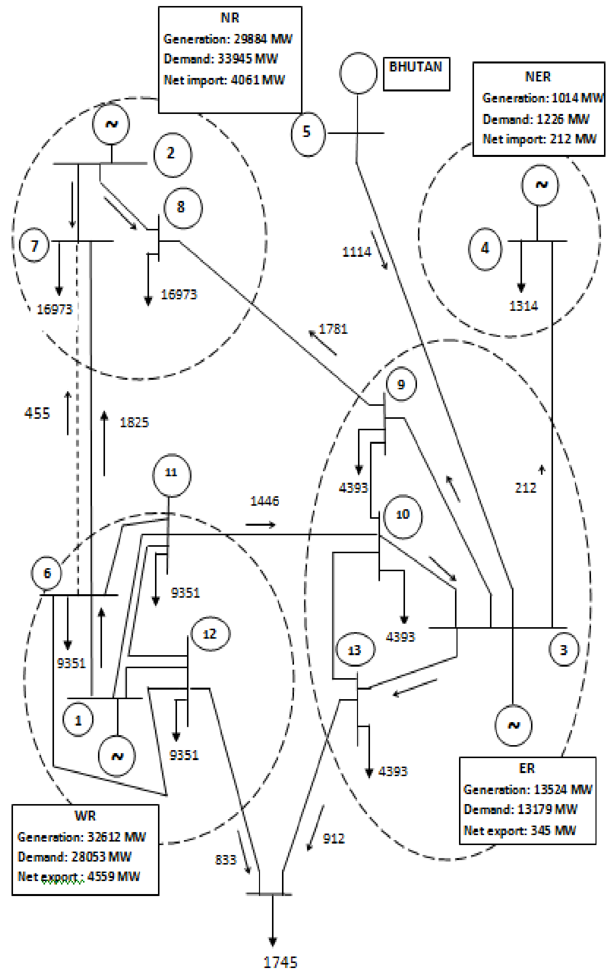

Fig. 5 Tie Line Flows on 31st July at 12.30 hrs

I. Discussion

The approach is outlined in the plots in Figures 6 and 7, which are helpful for evaluating the security of big grids that are heavily loaded. The influence of NR loading on the flows of the WR-NR tie line is greatest, followed by the WR-ER and ER-NR tie lines, as can be shown in Fig. 6. Fig. 7 depicts the impact of NR loading on average area-voltages. The average area voltage is calculated as the sum of all the bus voltages in the area. Here, too NR is affected to maximum extent. These charts can be checked online against the associated relay settings to evaluate overall security margin of the grid in almost real time. Calculations are non-iterative and suitable for early warning systems. As stated earlier, the iterative procedure currently in use is ill-suited for the purpose.

Table 1 Load in NR region increased in steps

Load at Load Buses in NR (MW)	WR-NR Tie Line (MW)	ER-NR Tie Line (MW)	WR-ER Tie Line (MW)	ER-NER Tie Line (MW)
16973 (Load at 12.30 hrs)	2280.1	1781.2	1446.6	212
17567	2588.4	2045.1	1489	191.7
18182	2897.4	2309.2	1531.5	171.4
18818	3206.4	2573	1574	151.1
19477	3516	2836.7	1616.7	130.8
20159	3825.5	3099.9	1659.3	110.5
20865	4134.8	3362.4	1701.9	90.2
21074	4224.3	3438.2	1714.2	84.3

Note: The last step increment in loads is taken at 1 %. This is done to get the power flow nearly equal to maximum capacity of WR-NR tie line.

Table 2Percentage Power Flow with respect of Maximum Capacity of tie lines

Change in Load in NR	WR-NR Tie Line (%)	ER-NR Tie Line (%)	WR-ER Tie Line (%)	ER-NER Tie Line (%)
Load at 12.30 hrs	54.03081	17.75872	32.95216	16.8254
3.50 % increase	61.33649	23.02293	34.8861	13.60317
7 % increase	68.65877	25.65304	35.85421	11.99206
10.50 % increase	75.98104	28.28215	36.82688	10.38095
14 % increase	83.31754	28.28215	36.82688	10.38095
17.5 % increase	90.65166	30.90628	37.79727	8.769841
21 % increase	97.98104	33.52343	38.76765	7.15873
22 % increase	100.1019	34.27916	39.04784	6.690476

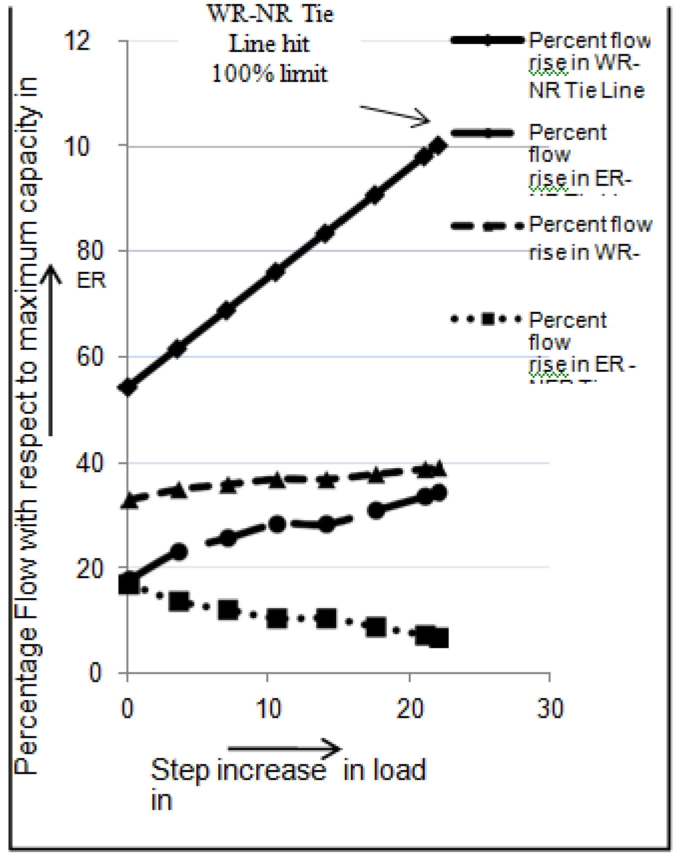

Fig. 6 Tie line-usage with increase in NR load

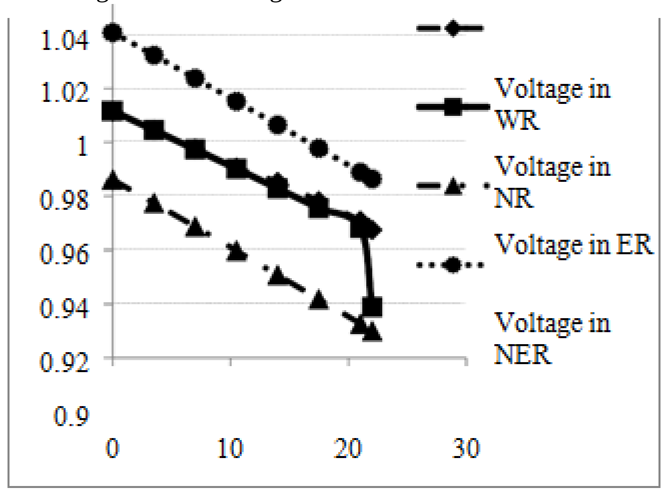

Fig. 7 Average of region-voltages with increase in NR load

Plots in Figures 6 and 7 give a system overview and are helpful for evaluating the security of heavily loaded large grids. As can be observed from Fig. 6, the WR-NR tie line experiences the greatest impact from NR loading, followed by the WR-ER and ER-NR tie lines. Fig. 7 depicts how NR loading affects average area-voltages. An area's average voltage is calculated as the sum of all of its bus voltages. Here, too, NR is severely impacted. Online comparisons of these graphs with the relevant relay settings can be utilised.

V. Acknowledgment

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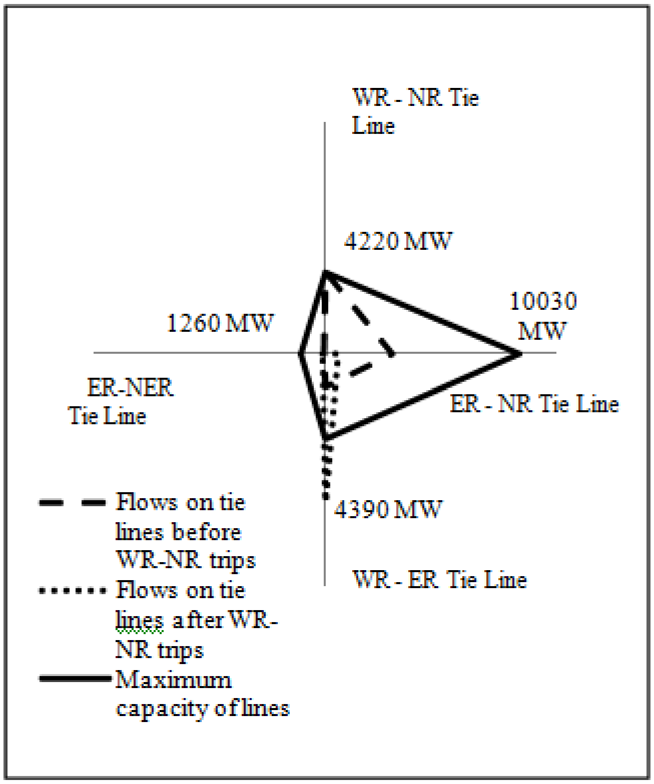

Fig. 8Tie Line flows before and after WR-NR Tie Line Trips

*Fig.3 is reproduced from http://indiainbusiness.nic.in/trade/presentation_loc/PGCIL.

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V. CONCLUSION

In order to analyse a grid disturbance, modular load flow is used. Modular Load Flow does not have the slack and PV bus limitations of iterative load flows, which are likely to blame for the load flow's inability to converge. Our explicit one step solution for early warning systems can take the role of time domain simulation, which is computationally expensive. The approach offers a system overview, has the ability to analyse contingencies, and may also be used for post-mortem investigations.

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