# Load Flow With Time Varying Injections

S D Varwandkar
VJ Technological Institute
Mumbai

Pragati P. Gupta
VJ Technological Institute
Mumbai

M V Hariharan
Indian Institute of Technology
Mumbai

***Abstract*—Renewable sources suffer from intermittency and variability in time and amount of power, causing problems of integration with the grid. Field experience in deregulated systems has occasionally shown that increase of renewable *injections* such as wind, solar etc. to the main grid *depresses* voltages at the point of interconnection. We pose the question: is it possible to analytically predict such behaviour at the planning stage? Conventional analytical techniques (load flow) do not seem to address this issue effectively. Bus classification of renewable generators and *apriori* specification of their voltages are difficult, and at times impossible. Conventional load flow techniques therefore fail to analytically construct future scenarios. We show that the behaviour mentioned above can indeed be predicted and online scenarios constructed with Modular Load Flow - a new load flow method reported in the recent past. With Modular Load Flow, time varying power flows and voltages can be calculated with time varying injections. We hope these studies to be useful in planning integration of renewables. To the best of authors' knowledge such 'tracking load flow' has not been reported earlier. A field experience has been explained analytically.**

***Keywords—load flow; integration of renewable sources; power system planning and operation***

## I. INTRODUCTION

Integration of renewable energy sources with main grid poses many operational problems. Sudden changes in difficult-to-control voltages occur. Firm power producers, traders and system operators therefore *do not like* renewable connections to main grid. However concerns of depleting fossil resources enjoin upon us to explore renewables and not ignore them for myopic advantages. Efforts therefore need to be directed towards meeting these challenges. Planning studies provide information about voltages and line flows given geographically scattered generations and loads. Load flow study has been an important tool for such studies. Renewable energy sources (RES) pose challenge to conventional iterative formulation on many accounts; PV type model is not suited due to requirement of specifying PV *apriori*. Wind generators are therefore modeled as PQ or RX [1]. Even in PQ type, the P-injections are difficult to specify with known degree of certainty. Optimization formulation as in OPF does not guarantee a solution. Solution through iterative procedure is therefore only a *possibility*. Incorrect specification of PV bus voltages may result in unsolvable cases [2]-[3]. Format of this paper is problem-solving type. First, a field experience is described. We then show that Modular Load Flow (MLF)-a recently reported method [4] – does not have these issues because of formulation and can solve low-voltage and ill-conditioned cases with equal ease. MLF does not treat generator buses *differently* (as PV and as slack). Several applications of MLF have been reported in [5]-[8]. What is remarkable about Modular Load Flow is that time varying injections can be easily incorporated into the MLF algorithm, i.e., *given time variation of injections, one can calculate time varying flows and voltages in the system.* We believe such a study has not been reported earlier.

## II. FIELD EXPERIENCE

Udumalaipet in Tamil Nadu (India), lies in an area of substantial wind generation and is connected to the southern grid. September is a month of high wind power generation. On a typical day (10-September 2014) time variation of wind generation and Udmalaipet voltage was recorded as shown in Fig. 1, extracted from [9].

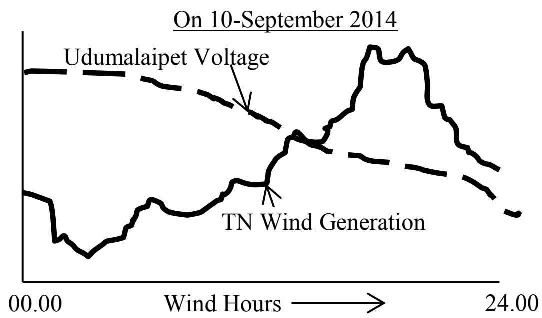


Fig. 1 TN Wind generation and Udumalaipet Voltage

It is observed that with increasing wind injection, voltages at points of interconnection (Udumalaipet) decline. Conventional load flow is ineffective for studying this type of behaviour. Considering the fact that voltage variations themselves are the objects to be studied, specifying voltage at the collector point *apriori* is obviously not correct. Modular Load Flow provides a good alternative. In the following section we show how time-series of line flows and voltages can be obtained for a given time-series of wind generations, using MLF. The illustrative example is not meant to represent this system in detail but is good enough to investigate the observed behaviour. With network parameters known, MLF can be used for any such system.

## III. Modular Load Flow With Renewables

Consider system shown in Fig. 2. It has main grid having two conventional generators; connected to a third one with renewable energy sources (RES). Line data and conventional generator data are shown in Table II and Table III. Time variation of generator at bus 5 is expressed is a time series,

$$P_{RES}(t) = \{P_{h1}, P_{h2}, ..., P_{hn}\} \quad (1)$$

For a typical time slot $P_{RES}(t)$ may be obtained from either the day-ahead forecast (for day-ahead assessment of security), or, from SCADA (operational values) for online assessment. Modular Load Flow finds flows and voltages in terms of injected powers. Premise of MLF is that turbine powers of generators are consumed in network elements in definite proportions called power fractions. The load-PQs are assumed to vary as square of the voltage and are replaced by their rated-voltage-impedances. The circuit including loads then becomes linear. For each element-generator pair of this circuit, power fractions can be determined from topology and parameters of network. Power consumption in an element is sum of the fractional powers supplied by the generators. For a snap-shot, generators are treated as constant power sources. Similarly, the line flows are also constant fractions of injected powers. Time-series of line flows and voltages are sequence of snap-shots of MLF results. Relevant expressions applicable to MLF are given below. Derivations can be found in [4].

$$\begin{aligned} p_{eif} &= \varepsilon_{eif} P_i \\ p_{ef} &= \sum_{i=1}^{ng} p_{eif} \\ \varepsilon_{eif} &= \text{Re}\left\{ \frac{1}{R_{ii}} \{\xi_{ei}(1)\xi_{ei}^*\} y_e^* \right\} \\ \xi_{ei} &= \{A^T Z\}_{ei}; \xi_{ei}(1) = \{A_1^T Z\} \end{aligned} \quad (3)$$

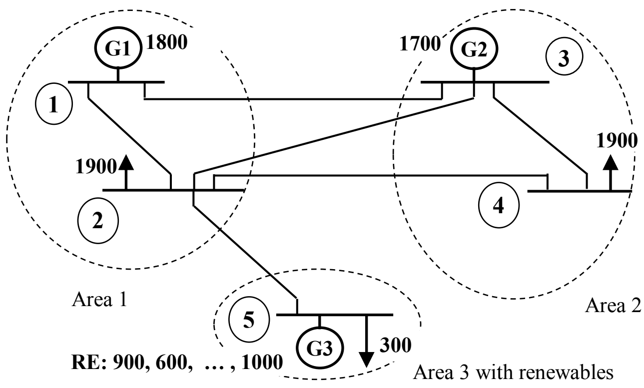


Fig. 2 A 5-bus Sample Grid network

In (3) $Z$ is the bus impedance matrix with loads included as circuit-impedances (RX) and the node-element matrix has been decomposed into two terms $A = A_1 - A_2$. Term $\varepsilon_{eif}$ is called *flow power fraction* of element *e* with respect to generator *i*.

$$\begin{aligned} p_e &= \sum_{i=1}^{ng} \varepsilon_{ei} P_i \\ \varepsilon_{ei} &= \text{Re}\left( \frac{1}{R_{ii}} \{\xi_{ei}\xi_{ei}^*\} y_e^* \right) \end{aligned} \quad (4)$$

Term $p_{ei}$ is power contribution of power injection $P_i$ in element *e* and $\varepsilon_{ei}$ is *loss fraction*. Constants $\varepsilon_{ei}$ and $\varepsilon_{eif}$ are obtained from topology and parameters of the network. Above expressions are then used to obtaining time-series of load flow solutions. Voltage across an element $r_e + jx_e$ is given by,

$$v_e = \sqrt{p_e r_e + q_e x_e} \quad (5)$$

In (5) $p_e$ is obtained using (4). In each element, the corresponding $q_e$ is obtained by,

$$q_e = \sum_{i=1}^{ng} \frac{x_e}{r_e} P_i \quad (6)$$

Symbol '*ng*' denotes number of conventional generators which can deliver reactive power. Voltage control mode operation of wind generator is not considered.

## IV. Illustrative Example

Let $P_{RES}(t)$ (wind) be given by time-series given in Table I. This is a 6-point approximation of the wind generation shown in Fig. 1 and represents a fairly realistic case.

TABLE I Renewable Source Generation

| Wind-hour | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| MW (G3) | 900 | 600 | 1100 | 800 | 1300 | 1800 | 1000 |

At wind-hour 1, firm generation in area 1 is 1800 MW (G1) and in area 2, 1700 MW (G2). Generator G3 is producing 900 MW. Time series for G3 is graphically shown in Fig. 3. MLF is conducted for every wind-hour. Since load-generation balance (which we assume at wind-hour 1) is to be maintained in load flow procedures, half the variable generation in excess of this value will be subtracted from G1 and G2 in equal amounts. There are two loads of 1900 MW each (at rated voltage) in area 1 and area 2. Load in area 3 is 300 MW. Impedances of loads are assumed to remain constant at their rated-voltage values. It is assumed that firm generations G1 and G2 have reactive capabilities of 100 MVAR and 90 MVAR respectively. Line data are shown in Table II. Load and generation data at wind-hour 1 are shown in Table III. Solution is obtained using equations (3)-(5) for power flows on the lines and bus voltages. These are shown in Fig. 4 and Fig. 5. Such solutions cannot be obtained by conventional load flow. MLF can get these accurately and without any worries about convergence.

*Algorithm*

*1. Convert all Q-specifications (generators, synchronous compensator and into rated-voltage- impedances).*
*2. Convert loads into their rated-voltage-impedances.*
*3. Compute bus impedance matrix. (We computed Y and inverted it. Bus building algorithm can alternatively be used.)*
*4. Use forecasted values of injection (for day-ahead calculations), or, obtain injected powers from SCADA (for online calculations).*
*5. Compute line flows using (3) and load-element-voltages using (5).*

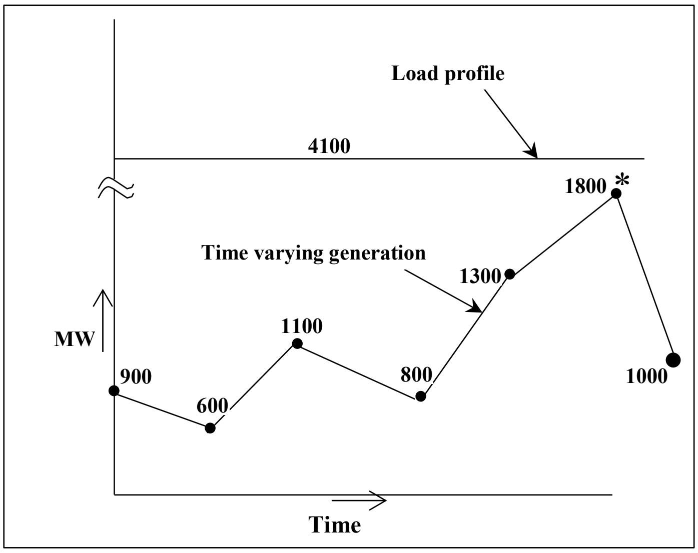


Fig. 3 Time varying generation and total load in a time-slot

TABLE II LINE DATA, PU

| No. | R | X | ½ B Charging |
|---|---|---|---|
| 1-2 | 0.01 | 0.04 | 0.003 |
| 1-3 | 0.01 | 0.03 | 0.0025 |
| 2-3 | 0.01 | 0.03 | 0.002 |
| 2-4 | 0.01 | 0.02 | 0.002 |
| 2-5 | 0.01 | 0.04 | 0.0015 |
| 3-4 | 0.01 | 0.03 | 0.002 |

TABLE III LOAD AND GENERATION DATA, MW

| Bus# | Load, MW |
|---|---|
| 2 | 1900*+$j$200 |
| 4 | 1900*+$j$200 |
| 5 | 300+$j$40 |

*To be adjusted equally for wind generation in excess of windhour#1

| Bus# | Gen. MW |
|---|---|
| 1 | 1800+$j$100 |
| 3 | 1700+$j$90 |
| 5 | Time-series of Table I |

Only topology and network parameters are needed to calculate power fractions which can be stored once for all for a given network structure. There is only one multiplication with the injection values for every element. There are no *faux pas* situations in modular load flow as in the conventional load flow, for example, *apriori* voltage specification at PV buses or choice of slack bus (and consequent non-uniqueness of solution) with the threat of non-convergence lurking around.

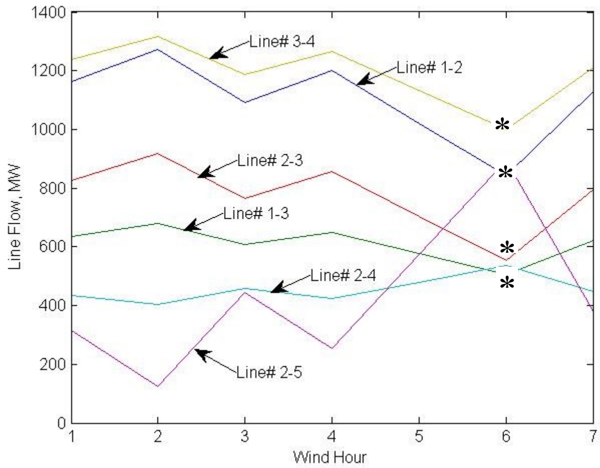


Fig. 4 Line Flows Time Series

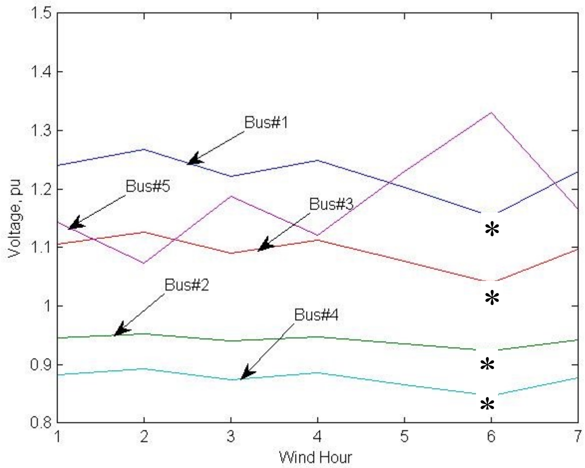


Fig. 5 Bus Voltages Time Series

## V. DISCUSSION AND CONCLUDING REMARKS

At wind hour 6 when the generation is at its peak (Fig.4), system voltages show a depression (Fig. 6). We recall this field experience mentioned at the beginning of the paper which was prima-facie confounding. Simulation with Modular Load Flow analytically confirms this behaviour. We consider this to be vindication of the premise on which the Modular Load Flow is based. Another important observation is that the wind-bus voltage and the line carrying wind power are prone to high fluctuations. This fact is known to power engineers but precise quantitative analysis has not been reported so far. Quantitative results during planning studies are useful for designing measures to counter undesirable behaviour (issue not addressed in the paper). Authors believe that the results could also be used online for designing controls using FACTS. Z-bus is computationally demanding but proposed closed-form solution avoids iterations and compensates for this computation by an order. Various attempts to formulate iterative optimal power flow with wind generators are not cited in the paper. The basis of Modular Load Flow is altogether different from that of the conventional formulation and any such attempt would invite criticism of unnecessary padding. We would conclude by saying that tools such as Modular Load Flow are now available to obtain guaranteed solution for quantitative results with time-varying bus injections - a characteristic feature of renewable sources.


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