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Evaluation of flexibility assessment indices upon flexible loading of thermal power plants with high penetration of renewables

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ABSTRACT

In this paper, power system flexibility assessment indices evaluation has been carried out with high penetration of renewables in MATLAB environment, inspired from IRENA FlexTool. The parameters such as magnitude of energy mix, resources available, electricity tariffs and price affordability play a vital role in the proposed research. The developed program has been tested against IEEE 9 bus and IEEE 39 bus systems with and without time-series data and with and without high penetration of renewables. By closely matching the results for various test cases and time series evaluations for IEEE 9 and IEEE 39 bus systems, the developed program has been benchmarked with the IRENA FlexTool and the comparisons have been charted out.

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1. INTRODUCTION

IRENA FlexTool is a flexibility assessment tool developed by international renewable energy agency (IRENA). The IRENA FlexTool is a freeware available in IRENA website. It can be used for flexibility assessment studies and economic impact of high penetration of renewables. Later, it has been benchmarked with various other propriety software such as REFLEX and RESOLVE. Also, this FlexTool has been used to provide flexibility assessment studies for grid systems of Panama, Columbia, and Uruguay.

Huge additions of renewable energy generation into power systems are being made to reduce the environmental impact caused by power generation. Despite its benefits, higher renewable energy penetration may likely create additional problems such as system instability and unpredictability. With the help of IRENA FlexTool simulator, common industry test standards such as IEEE 9 bus and IEEE 39 bus systems were built using standard generation and load data. Several optimal power flow studies were performed on the mentioned test systems with and without the inclusion of an energy storage system. Incremental change in total system cost due to addition of energy storage is estimated and the effect of energy storage on isolated system with renewable energy is observed.

The software packages such as IRENA FlexTool, RELEX and RESOLVE, are propriety in nature. Hence to make any studies on the grid flexibility, the user has to buy them or develop their own program. The input formats have to be provided in pre-defined formats and there is very little flexibility provided to the user. Also, these software packages are to be modified for each country, as the energy mix and the resources available in each country is altogether different. The parameters such as magnitude of energy mix, resources available, electricity tariffs and price affordability play a vital role in the proposed research. Lacking of an own program/code has led to dependency on software/packages available in the market/industry.

Considerable amount of research has gone into various simulators/softwares. Lack of own program/code has led to dependency on software/packages available in the market/industry. Hence, a new program has been proposed for carrying out the flexibility studies and optimal power flow study has been worked out. In the proposed work, a program has been developed in MATLAB environment, inspired from IRENA FlexTool. This developed program works in line with the FlexTool, such as input templates, input formatting, GUI, results excel workbooks, comprehensive display through graphs. The developed program has been tested against IEEE 9 bus and 39 bus systems with and without time-series data and with and without high penetration of renewables.

2. LITERATURE REVIEW

A literature review has been conducted over the broader area of research "Increased Renewable Generation and Assessment of Flexibility Assessment Indices there-of". The district heating concept has been explained in [1]. The co-generation of district heating has been discussed and wind curtailment philosophy proposed. A case study inspired from Germany was discussed and technical problems faced in two shift operations were explained in [2]. Also, quantifying limits and costs of cycling of power plants through mathematical modeling had been explained. Different types of starts (cold/warm/hot) along with their procedures in a power plant have been discussed along with the cost analysis of cycling mathematically in [3]. Also the work presented in [3] has widely examined a test case scenario of Ireland.

System flexibility had been assessed by using the metrics such as ramp rate, duration of ramp, power capacity and energy capacity in [4]. Mathematical modelling of grid flexibility has been explained and various methodologies of supporting flexibility had been discussed. Lund *et al.* [5] presented that system flexibility has been assessed using the metrics such as ramp rate, ramp frequency and response time.

Denholm and Hand [6] discussed flexibility related economic issues in US and estimated the tariff increase vis-à-vis increase in renewable generation accordingly. Gonzalez-Salazar *et al.* [7] reviewed operational flexibility of various types of power plants and discussed advantages of gas-fired plants over coal-fired plants, discussed comparison for different types of startups. A comprehensive system flexibility optimization strategy has been proposed, with a clear outlook of planning, operation and management in [8]. Also, it discussed flexibility assessment indices and their mathematical evaluation.

Small signal studies using eigen value analysis for Queensland network with and without wind energy has been discussed elaborately in [9]. Practical application of flexibility studies using eigen value analysis has been applied to Queensland network. Alizadeh *et al.* [10] proposed hierarchy of various flexibility systems have been established, particularly, the energy storage options have been classified. Also, it discussed flexibility requirements in power systems due to variable renewable generation. Further, it discussed steps taken by foreign countries for enhancing flexibility.

Ma *et al.* [11] proposed an algorithm for evaluating flexibility in power systems. This algorithm combines long-term investment along with short-term operation costs to evaluate the optimal construction of flexible generating units. Also, Profitability of flexibility and its economics have been discussed. The work in [12], which is based on a set of seven case studies involving 15 countries, discusses system flexibility at the grid level and inter-grid connectivity.

Kondziella and Bruckner [13] reviewed various scientific approaches that have been implemented in flexibility demand studies, w.r.t Germany and European power systems. Also, it has discussed various options to improve system flexibility. Inertia calculation of systems with various generation mix has been discussed and inertia of systems with high VRE was explained in [14].

2.1. Flexibility assessment indices

Following indices [8] have been used for flexibility assessment: i) periods of system flexibility deficit (PFD); and ii) insufficient ramp resource expectation (IRRE). PFD is defined as the periods of system flexibility deficit, which is mainly used in unit commitment and economic load dispatch [8]. The probability of insufficient flexibility available to a grid operator at each point in time is the cumulative probability of the required ramping rate that the system will be unable to provide due to the net load change at a circumstance and point of time [12].

2.2. Definition of flexibility indices

$O_{t,h,s}$ is computed as adjustable maximum output of complete system at a considered circumstance (for a selected combination of renewable energy sources) and time period:

$$O_{t,h,s} = \sum_{r=1}^{R} F_{r,t+h,s} - \sum_{r=1}^{R} F_{r,t,s} + \sum_{v=1}^{V} R_{v,t+h,s} - \sum_{v=1}^{V} R_{v,t,s} \quad (1)$$

where r is the index number of the flexibility resource (for ex thermal generation), R is total count of the flexibility resource, t is index number of the period, h is the length of the period, s is index number of the circumstance, v is index number of variable renewable generation (for ex solar generation), V is total count of variable renewable generation, $F_{r,t+h,s}$ is output of the flexibility resource r at the circumstance s in the period t+h and $R_{v,t,s}$ is output of variable renewable generation v at the circumstance s in the period t.

Next, $N_{t,h,s,+/-}$ is defined as the upward/downward flexibility of system at the considered circumstance and period.

$$N_{t,h,s,+} = O_{t,h,s} - E_{t,+} - L_{t,h} \quad (2)$$

$$N_{t,h,s,-} = L_{t,h} - E_{t,-} - O_{t,h,s} \quad (3)$$

Where $E_{t,+/-}$ is emergency reserve capacity of the system at time t and $L_{t,h}$ is the estimated net difference between the two periods. Set periods when in (2) or (3) is less than 0 as $T_{h,+/-}^{PFD}$. Hence, the flexibility quantitative (upward or downward) index in a certain period is (4).

$$T_{h,+/-}^{PFD} = Mean\left(T_{s,h,+/-}^{PFD}\right) \quad (4)$$

Periods of flexibility deficit (PFD) is calculated as the average value of the system at different circumstances [8].

2.3. Calculation of PFD and IRRE

Following steps are followed in the sequential manner to calculate IRRE [12] as shown in Figure 1. $NR_{t,i,+/-}$ is defined as net load ramp at period t in either direction [12]. $AFD_{i,+/-}$ (X) function is estimated as available flexibility distribution, which is discrete cumulative distribution function of the available flexibility, X [12].

$$IRRP_{t,i,+/-} = AFD_{i,+/-}\left(NR_{t,i,+/-} - 1\right) \quad (5)$$

The cumulative sum of the values of IRRP over the entire time series, T+/−, for either direction, provide us the insufficient ramping resource expectation, as shown (6) [12].

$$IRRE_{i,+/-} = \sum_{\forall t \in T_{+/-}} IRRP_{t,i,+/-} \quad (6)$$

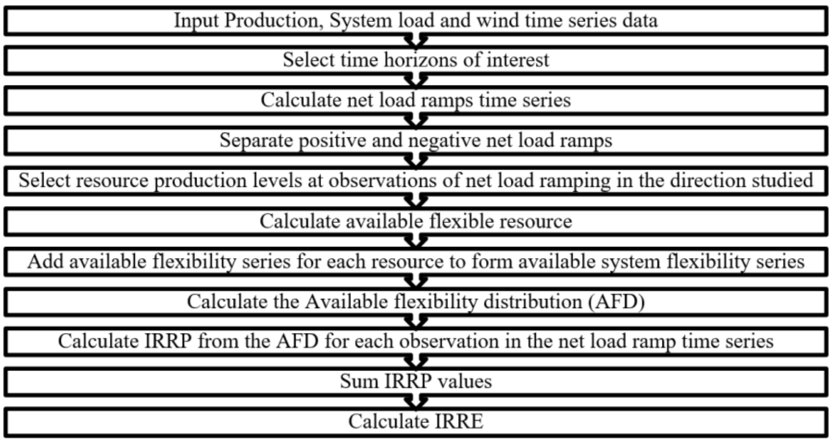

Figure 1. Steps for calculation of IRRE

2.4. Advantages and drawbacks of PFD and IRRE

Following are the advantages of PFD and IRRE: i) The calculation steps and procedures are identical to each other; ii) Both the indices show the flexibility (upward and downward) quantitatively and also the flexibility index of all resources of the system during certain circumstance and period [8]; and iii) It provides the direction of increasing system flexibility and guides us in flexibility resources optimization [8]. One common disadvantage of PFD and IRRE is the distribution system flexibility and demand side management (load side) are not considered and cannot be evaluated [8].

2.5. Observations

From the literature [14]–[23], it can be observed that most researchers reviewed the present energy mix scenario in various countries, analyzed the various factors affecting the grid stability there upon and discussed the methods to quantify grid flexibility. Few authors identified the flexibility assessment indices and proposed algorithms to increase the grid flexibility [24]–[27].

2.6. Motivation and objective of paper

Even though a lot of research has been done in foreign countries, not much literature was found in the Indian scenario. Also, the energy mix and the resources available of each country is altogether different. The parameters such as magnitude of energy mix, resources available, electricity tariffs and price affordability play a vital role in the proposed research.

Considerable amount of research has been done using various Simulators/Software. Lacking of an own program/code has led to dependency on software/packages available in the market/industry. With the help of own program, it was envisaged that a lot of novelty can be brought in. Hence it was proposed to develop a new program on par with IRENA FlexTool. The program can be later benchmarked with the said software/packages with test systems over various iterations. After rigorous testing and validating the results, the program shall be used for bigger Indian practical systems where much research has not been carried upon.

3. METHODOLOGY

3.1. Algorithm of the program

This study aims to calculate the value addition made by ESS to the power system with renewable energy, by analyzing how storage systems affects the flexibility of an isolated power system. Specifically, the objective was to find out the economic importance of size and location of the storage system in the network. To achieve this, program was developed that can simulate the dispatch of generation in a practical power system. Flexibility of individual generator is calculated as (7).

$$flex(i) = \frac{\frac{1}{2}[P_{max}(i) - P_{min}(i)] + \frac{1}{2}[R_{amp}(i) \cdot \Delta t]}{P_{max}(i)}, \forall i \in N \tag{7}$$

Flexibility of complete system is calculated as (8).

$$FLEX_N = \sum_{i \in N} \left[\frac{P_{max}(i)}{\sum_{i \in N} P_{max}(i)} \times flex(i) \right], \forall i \in N \tag{8}$$

After this, a simple iterative procedure was required to utilize the IRENA FlexTool to estimate the system costs of the IEEE 9-bus test system with the addition of the pumped hydro storage (PHS) model. The following procedure was used to simulate the multiple cases of added PHS in the IEEE-bus test system, while changing both the size of storage and location of the added storage system.

i) Add pumped hydro storage (PHS) model into IEEE-test system.
   a. Connect pumped hydro storage (PHS) model to renewable energy generation (REG) bus.
   b. Set size of pumped hydro storage (PHS) to 10 MW and calculate the cost model.
ii) Perform time series OPF to calculate cost per hour of power system.
iii) Log results into excel spreadsheet.
iv) Increase storage size of pumped hydro storage (PHS) by 10 MW and re-calculate the cost model.
v) Repeat steps ii)-iv) until storage size reaches the total size of renewable energy generation (REG) connected.
vi) Disconnect pumped hydro storage (PHS) model at the current bus, choose a different bus and repeat as earlier in step i).
vii) Repeat steps i) point b-vi), for all the buses except for the slack bus.

3.2. Flow chart of the program

The flowchart of the program is shown as in Figure 2. It has 14 steps which can be classified as four sections. The first section is network identification as given by steps 1-3. Second section is constraints identification, i.e., steps 4-5. The third section is OPF and incremental change in energy storage at given location from steps 6-11. The last section is bus location change as indicated in steps 12-14.

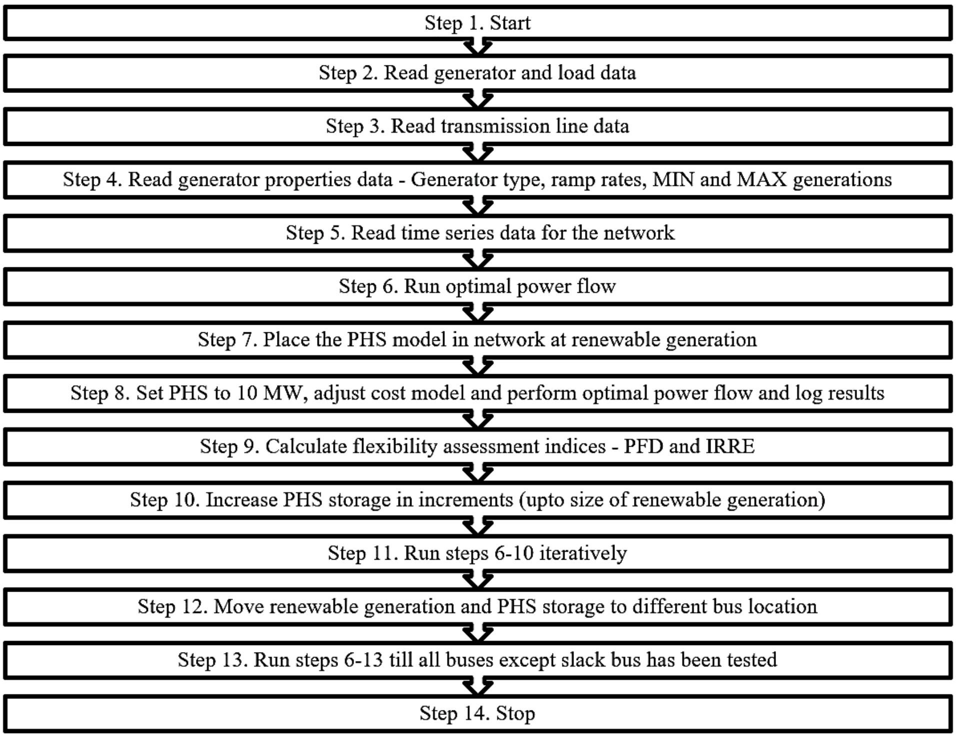

Figure 2. Flow chart of the proposed program

3.3. Case studies: IEEE 9 bus and IEEE 39 bus systems

The IEEE 9 bus system, the detailed generator data, transmission line data and load data considered is shown in Figure 3, Tables 1 and 2. The IEEE 39 bus system and the detailed generator data considered is shown in Figure 4 and Table 3. The wind generation time series used is shown in Figure 5. The transmission line data of the IEEE 39 bus system considered is shown in Table 4. The wind and hydro generation time series used is shown in Figure 6.

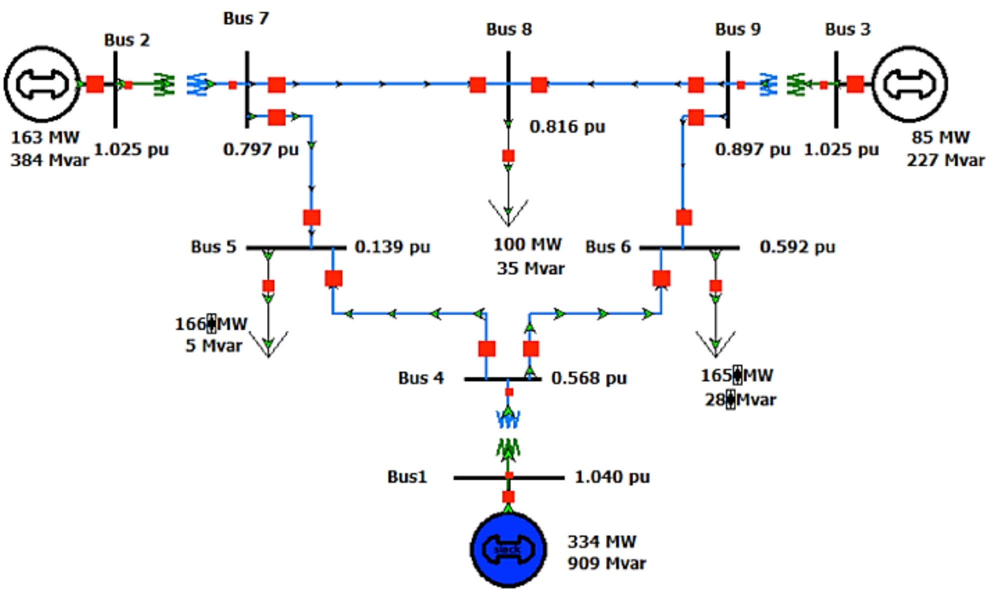

Figure 3. IEEE 9 bus system [22]

Table 1. IEEE 9 bus system-generator data [22]

Parameter	M/C1	M/C2	M/C3
Rated Power [MVA]	247.5	192	128
H [sec.]	23.64	6.4	3.01
X_d [pu]	0.146	0.8958	1.3125
X_d' [pu]	0.0608	0.1198	0.1813
X_q [pu]	0.0969	0.8645	1.2578
X_q' [pu]	0.0969	0.1969	0.25
T_{d0}' [sec]	8.96	6.0	5.89
T_{q0}' [sec]	0.31	0.535	0.6

Table 2. IEEE 9 bus system transmission line data [22]

	Series Z [pu]		Shunt Y [pu]
Bus to bus	*R*	*X*	*B*
Trans. 1-4	0.0	0.0576	
Trans. 3-9	0.0	0.0586	
Trans. 2-7	0.0	0.0625	
Line 4-5	0.01	0.085	0.176
Line 4-6	0.017	0.092	0.158
Line 5-7	0.032	0.161	0.306
Line 6-9	0.039	0.170	0.358
Line 7-9	0.0085	0.072	0.149
Line 8-9	0.0119	0.1008	0.209

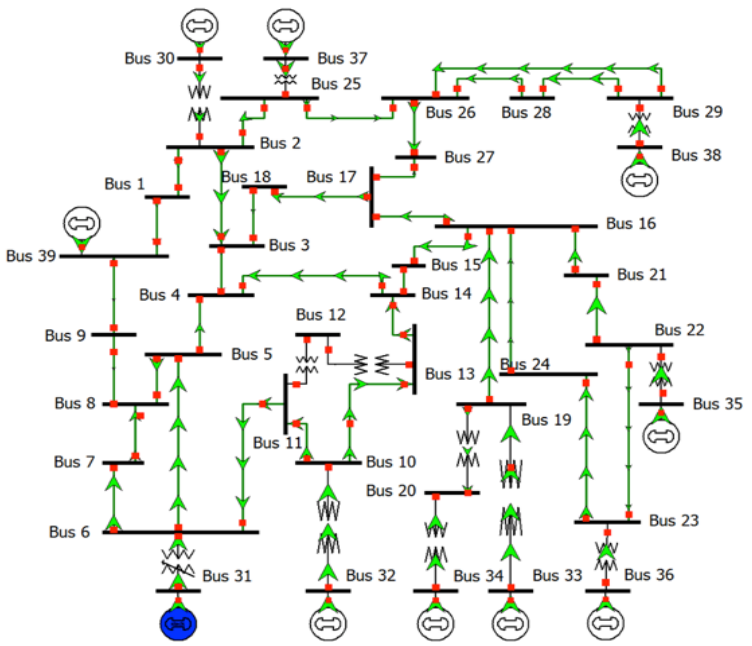

Figure 4. IEEE 39 bus system [23]

Table 3. Detailed model unit data for IEEE 39 bus system [23]

Unit No.	H (sec)	R_a	x_d'	x_q'	x_d	x_q	T_{d0}'	T_{q0}'	x_l'
1	500.0	0	0.006	0.008	0.02	0.019	7.0	0.7	0.003
2	30.3	0	0.0697	0.170	0.295	0.282	6.56	1.5	0.035
3	35.8	0	0.0531	0.0876	0.2495	0.237	5.7	1.5	0.0304
4	28.6	0	0.0436	0.166	0.262	0.258	5.69	1.5	0.0295
5	26.0	0	0.132	0.166	0.67	0.62	5.4	0.44	0.054
6	34.8	0	0.05	0.0814	0.254	0.241	7.3	0.4	0.0224
7	26.4	0	0.049	0.186	0.295	0.292	5.66	1.5	0.0322
8	24.6	0	0.057	0.0911	0.290	0.280	6.7	0.41	0.028
9	34.5	0	0.057	0.0587	0.2106	0.205	4.79	1.96	0.0298
10	42.0	0	0.031	0.008	0.1	0.069	10.2	0.0	0.0125

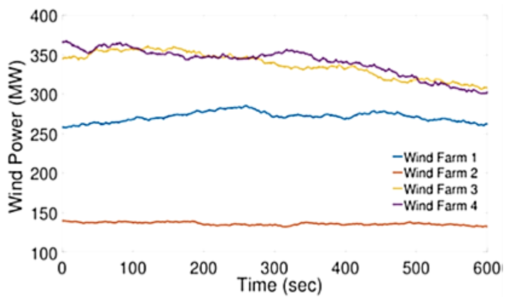

Figure 5. Wind power generation time series sample

Table 4. IEEE 39 bus system transmission line data [23]

Unit No.		X [pu/m]	R [pu/m]	B [pu/m]	Unit No.		X [pu/m]	R [pu/m]	B [pu/m]
From bus	To bus				From bus	To bus			
1	2	0.0411	0.0035	0.6987	13	14	0.0101	0.0009	0.1723
1	39	0.025	0.0010	0.7500	14	15	0.0217	0.0018	0.3660
2	3	0.0151	0.0013	0.2572	15	16	0.0094	0.0009	0.1710
2	25	0.0086	0.0070	0.1460	16	17	0.0089	0.0007	0.1342
3	4	0.0213	0.0013	0.2214	16	19	0.0195	0.0016	0.3040
3	18	0.0133	0.0011	0.2138	16	21	0.0135	0.0008	0.2548
4	5	0.0128	0.0008	0.1342	16	24	0.0059	0.0003	0.0680
4	14	0.0129	0.0008	0.1382	17	18	0.0082	0.0007	0.1319
5	6	0.0026	0.0002	0.0434	17	27	0.0173	0.0013	0.3216
5	8	0.0112	0.0008	0.1476	21	22	0.0140	0.0008	0.2565
6	7	0.0092	0.0006	0.1130	22	23	0.0096	0.0006	0.1846
6	11	0.0082	0.0007	0.1389	23	24	0.0350	0.0022	0.3610
7	8	0.0046	0.0004	0.0780	25	26	0.0323	0.0032	0.5130
8	9	0.0363	0.0023	0.3804	26	27	0.0147	0.0014	0.2396
9	39	0.0250	0.0010	1.2000	26	28	0.0474	0.0043	0.7802
10	11	0.0043	0.0004	0.0729	26	29	0.0625	0.0057	1.0290
10	13	0.0043	0.0004	0.0729	28	29	0.0151	0.0014	0.0249

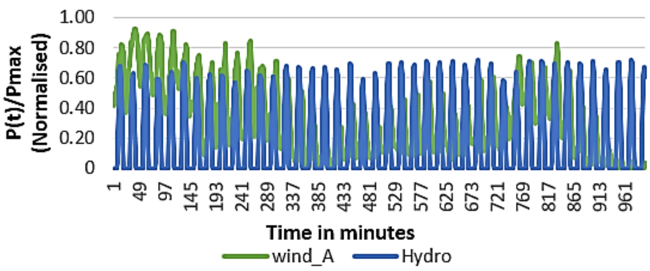

Figure 6. Wind and hydro generation time series sample

4. RESULTS AND DISCUSSIONS

4.1. Figures and tables

Multiple iterations have been carried out on both IEEE 9 bus and IEEE 39 bus systems using both the IRENA FlexTool and the proposed program. Few sample results obtained through simulating different IEEE test cases are identified and shown Figures 7-10. Figure 7 and Figure 8 shows the results of IRENA FlexTool and Figure 9 and Figure 10 shows the results obtained through the proposed program against the same input data.

Figure 7 shows the power generated by types of generation vs time, obtained in IRENA FlexTool. Figure 8 shows the total units generated vs type of generation, obtained in IRENA FlexTool. Figure 9 shows the power generated by types of generation vs time, obtained in our proposed algorithm. Figure 10 shows the power generated by types of generation vs time, obtained in our proposed algorithm.

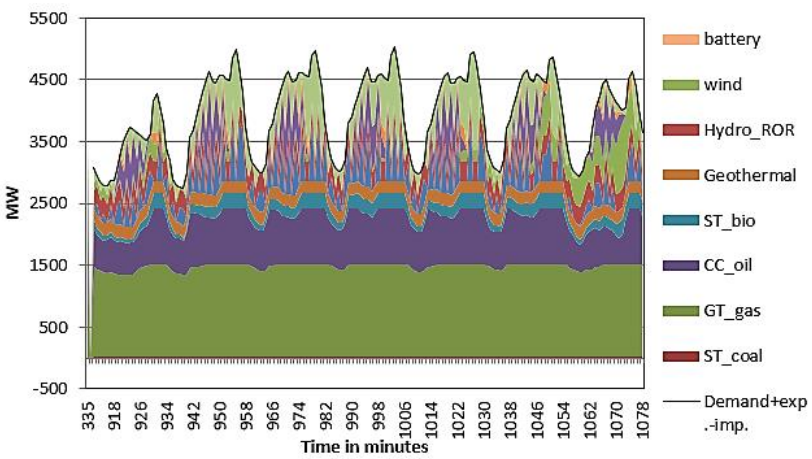

Figure 7. Results of IRENA FlexTool (generation vs time)

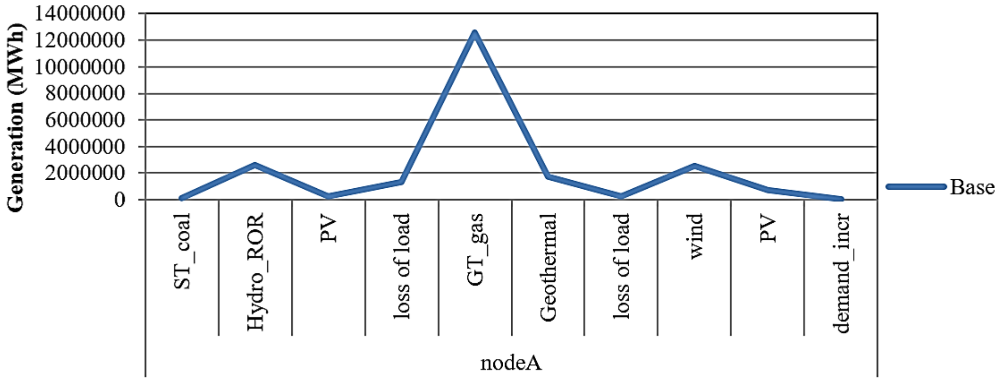

Figure 8. Results of IRENA FlexTool (generated units vs generation type)

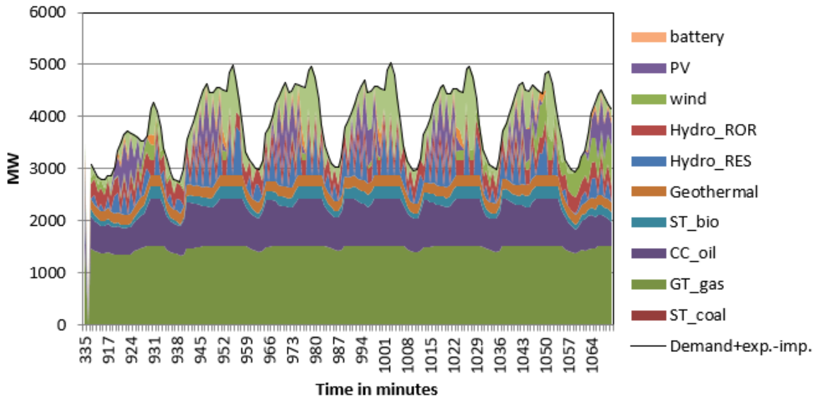

Figure 9. Results of proposed program (total generation vs time)

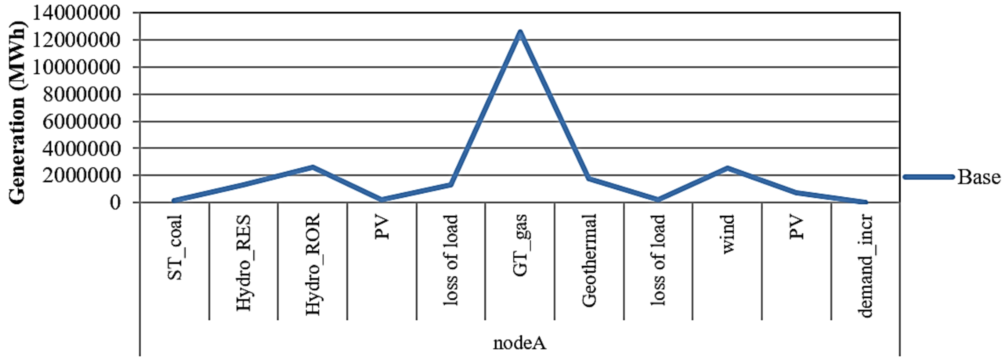

Figure 10. Results of our program (generated units vs generation type)

4.2. Comparison with IRENA FlexTool

The results obtained using the proposed algorithm have been compared with that of IRENA FlexTool over the test cases of IEEE 9 bus and IEEE 39 bus systems. The comparison has been charted out taking the generation (GWh) and cost (USD/year) as parameters and is shown in Table 5. It was also observed that the values of flexibility indices in both the IRENA FlexTool and the proposed algorithm have always come out to be exactly the same. The comparison in Table 5 helps us to benchmark the proposed program against the IRENA FlexTool. The comparison between nature of the IRENA FlexTool and the proposed program is shown in Table 6. Various advantages of the proposed program over the simulator/software have been shown.

Table 5. Weighted average error of generation and cost

System	IEEE 9 bus		IEEE 39 bus	
Scenario	Time series only	Time series & VRE	Time Series only	Time series & VRE
Comparison parameter	Generation (GWh)	Cost (USD/yr)	Generation (GWh)	Cost (USD/yr)
IRENA FlexTool	0.1%	0.09%	0.7%	0.3%
Proposed algorithm	0.1%	0.08%	0.7%	0.2%

Table 6. Comparison of IRENA FlexTool and proposed algorithm

Parameter	IRENA FlexTool	Proposed algorithm
Ownership	Third-party (IRENA)	Self-developed
Modifications	Only to GUI Extent	All changes possible
Purpose	Open-market software, sold to OEMs	Self-research oriented
Results	Applied to various country scenarios (practical systems) and benchmarked with REFLEX and RESOLVE	Benchmarked with IRENA Flextool in this work
Inputs & outputs	Excel templates only	Excel or text files in pre-defined format
Working methodology	Runs batch codes and executable for which source code isn't available	Runs developed subroutines/functions

5. CONCLUSION

By closely observing and comparing the results for various test cases and time series evaluations for IEEE 9 and IEEE 39 bus systems, the developed program has been benchmarked with the IRENA FlexTool and the comparisons have been charted out. This developed program can now be used for bigger and complex systems. Also, the developed program can be modified and used for multiple renewable energy resources and single or multiple energy storage systems. Further research can be carried by testing the program on practical Indian systems and assess the grid response and flexibility indices upon increasing penetration of renewable generation.

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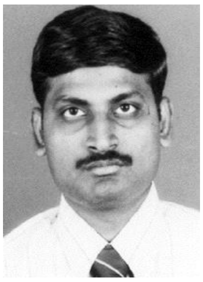

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