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# Flexibility Requirements for Renewable Integration in Power Systems

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***Abstract*—This paper addresses the issue of generation flexibility in power systems integrating renewable energy. The focus is on additional flexibility requirements associated with the generation scheduling domain, which is mainly relevant to the hourly variation and uncertainty of renewable power output. A normalized flexibility index is used to estimate the flexibility level of single units and indicate their contribution to the whole system's flexibility. An interval-based generation scheduling is proposed based on a short-term unit commitment algorithm. The study treats the case of Tunisia, applied on a target day with real measurements.**

***Keywords—Power system, flexibility, variabile renewable energy, ramp-rate, generation scheduling, unit commitment.***

## I. Introduction

Power systems are undergoing a remarkable transition towards high shares of renewable energies in the electric power pool [1]. Variable Renewable Energies such as solar photovoltaic and wind are among those exhibiting non-dispatchability features. Indeed, variability and uncertainty are two characteristics of variable renewable energies affecting directly the operational reliability of power systems, and thus setting barriers to reach the envisioned PV/wind share of global electricity by 2050 [2]. An immediate concern relates to the ability of a power system to accommodate variable generation, while maintaining a reliable balance of supply/demand at a reasonable cost.

Flexibility is such a property of a power system reflecting its ability to respond to the variability of its net load, which is the load minus the contribution of variable Generation [2]. Fig. 1 demonstrates intermittency and variability of wind power generation in the power system of Tunisia recorded during three candidate days of January and July 2014. Such variability adds a supplementary unscheduled load to the grid. For instance, the integration of 100 MW of wind without increase in net load, releases conventional units of the same quantity. This reduction will be constrained by their minimum stable generation, and it can be expected that, for certain

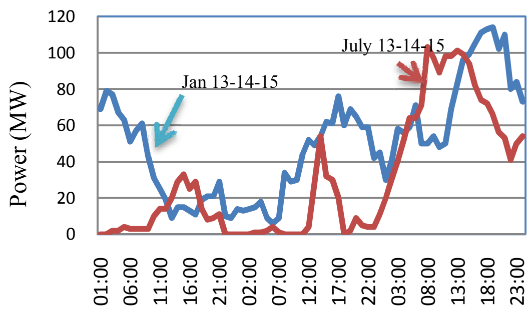


Fig. 1 Wind power variability

levels of low net-demand, renewable curtailment may be the only source of flexibility. Upon its extinction, the network is loaded with an additional 100 MW. This load is dispatched from the most flexible conventional sources. Such increase in demand calls for more flexibility because of the stochastic nature of variable resources. As a result, a "flexibility gap" is created and needs to be covered by other flexibility options. For this reason, the operational planning strategies are changing and the question is no longer how many resources available to cover the power demand, rather how many flexible resources available to cover demand forecasting. Limited flexibility can result in increased operational cost, reduced operational value of variable generation, including renewable curtailment, or the need for additional flexible conventional capacity to meet reserves or peak demand [3].

Five key options for flexibility stand out [4]: Production, demand, storage, network and production units. Each key is optimal for a given time. The optimization of production plans is done using a well-defined. "unit commitment" algorithm, that is a linear algorithm that takes into consideration the generation costs of conventional units. Generation cost minimization includes: fuel and incremental costs, taking into account the following constraints: system demand, spinning reserves, ramp rates and minimum start-up/shutdown times.

The goal of this paper is to assess the flexibility of the Tunisian power system for an increased share of variable


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## II. Flexibility definition and metrics

We may conceptually consider the flexibility of a power system, of a generation mix, and of a single generator. Ramp up and ramp down rates in reserve deployment stand out as key factors for flexibility. A flexible power system should have sufficient capability to cope with the predicted variations in net demand and have sufficient ramping and enough operating reserve to fulfill the forecasted gap. The flexibility of a conventional generation mix can be defined as its ability to follow the changes in net demand at different time scales. For each generator, its ability to provide upward load following is limited by its ramp-up rate and the spare capacity between their scheduled output and their maximum capacity. Likewise, their ramp-down rate and the difference between their scheduled output and their minimum stable generation (MSG) limit their ability to provide downward reserve. The ramping capability is part of the operating reserve constraint and therefore the proposed index will be developed based on the study of operating reserve.

A flexibility index can be defined for each conventional generator $i$ :

$$flex(i) = \frac{\frac{1}{2}[P_{max}(i)-P_{min}(i)]+\frac{1}{2}[Ramp(i)\cdot\Delta t]}{P_{max}(i)} \quad (1)$$

where $P_{max}(i)$ and $P_{min}(i)$ are the maximum capacity and the minimum stable generation of conventional generator $i$. $\frac{1}{2}[Ramp(i)\cdot\Delta t]$ is the average value of $[Ramp\_up(i)\cdot\Delta t]$ and $[Ramp\_down(i)\cdot\Delta t]$, and thus indicates the speed at which a unit can adjust its output within $[P_{max}(i)-P_{min}(i)]$. To allow comparisons, the index is normalized to account for the variable sizes of the units. The flexibility index of a whole system A is then defined as the weighted sum of the flexibility indices $flex(i)$ of the individual generators. The weighting factors are taken as equal to the capacity contribution of each unit. The whole system flexibility is thus:

$$FLEX_A = \sum_{i\in A}\left[\frac{P_{max}(i)}{\sum_{i\in A}P_{max}(i)}\times flex(i)\right]\ \forall\, i\in A \quad (2)$$

The flexibility index determines whether a system is flexible or not, and whether a unit is flexible: By comparing the index of flexibility for a particular unit of production with the index of flexibility of everything the system, one can say that a unit is flexible or not and how much this unit contributes for total flexibility. If the index of flexibility for a unit is greater than the unit is greater than that of the system then the unit is considered flexible and vice versa, non-flexible units are those with a flexibility index lower than that of the system . This same term of flexibility makes it possible to group the flexible and non-flexible units into three groups according to the field of use after: the HFM "highly flexible mix" which is a mix between units with greater index of flexibility, the MFM "medium flexible mix" is the units with a moderate index of flexibility or a mix between strong and weak index and finally the LFM "low flexible mix" which groups the units with low index of flexibility. The choice of these three categories is made by field of use and according to the market day ahead and real time balancing market. These three groups exist to remedy the intermittent production of renewable energies..

## III. Unit Commitment with flexibility

Flexibility requirements ought to be incorporated in the system unit commitment process. [5]- [7].

### *3.1 Objective Function*

The objective function must include not only the operating cost but also the investment cost of candidate generating units, amortized over the optimization horizon. The objective function is:

$$min\left(\sum_{i=1}^{N}\sum_{t=1}^{T}OC_{i,t}+e_j\left(\sum_{j=1}^{A}\sum_{t=1}^{T}AOC_{j,t}+\sum_{t=1}^{T}AIC_j\right)\right) \quad (3)$$

Here $OC_{i,t}$ is the operational cost of the existing unit $i$ at time $t$; $AOC_{j,t}$ is the operating cost of the additional unit $j$ at time $t$; and $AIC_j$ is the investment cost of unit $j$ amortized over the optimization horizon. $e_j$ is the binary decision variable which indicates whether the additional flexible unit $j$ should be built.

### *3.2 Constraints*

*a) System constraints*

- *Power balance*:

$$\sum_{i=1}^{n}p_{i,t}u_{i,t}+[W_f(t)-w_c(t)]+[S_f(t)-s_c(t)]=L_f(t) \quad (4)$$

- *Spinning reserve requirements:*

$$R_{up}(t)\ge \max[u_{i,t}P_{i,max}]+3\sigma_{nl}(t) \quad (5)$$

$$R_{down}(t)\ge \max[u_{i,t}P_{i,max}]+3\sigma_{nl}(t) \quad (6)$$

*b) Thermal unit constraints*

- *Generation maximum and minimum limits:*

$$P_{i,min}\le p_{i,t}\le P_{i,max} \quad (7)$$

- *Ramp rate constraints*

$$p(i,t+1)-p(i,t)\le Ramp_{up}(i)\Delta t \quad (8)$$

$$p(i)-p(i,t+1)\le Ramp_{down}(i)\Delta t \quad (9)$$

## IV. Flexibility Assessment of the Tunisian Power System

### *4.1 System description*

Tunisia is an energy-dependent country with modest oil and gas reserves. Around 94 percent of the total energy is produced by natural gas and oil, while renewable contributes merely 6% of the energy mix. The installed electricity capacity at the end of 2015 was 5,695 MW which is expected to sharply increase to 7,500 MW by 2021 to meet the rising power demands of the industrial and domestic sectors [8]. Additional conventional power plants are being built, while developing solar and wind capacities to sustain economic development. Under new plans, Tunisia has committed to generating 30 per cent of its electricity from renewable energy sources in 2030 [8].
Interconnection are reliable options for adding flexibility to the network. The current interconnection ensures a link to Algeria with a power of 220 MW transported by means of a HVAC tie line. A future project, prospects 1200 MW power exchange with Italy [9] by 2020.

Fig. 2 schematizes a reduced model of the Tunisian transmission system limited to 21 buses-9 generators, which buses are shown in Table 1. The percentage of installed capacity per fuel type is shown on Fig. 3. As the figures show production in electricity is based on fuel plants. Power stations in Tunisia are mainly steam turbines, gas turbines and combined cycle gas turbines.

### *4.2 Flexibility indices determination*

Table 1 presents the ramping rated of the different generation units. The flexibility indices have been computed accordingly for short-term time horizons: 5 and 15 minutes. From the Table, we note that the flexibility index for a 15-minute forecast horizon for gas turbiness is almost 100% which remains for longer horizons. For the index "flex up" it is lower than 100%, and can increase for longer forecast horizons. For the flexibility index of the frame 5 minute, the index is lower than 50% in most cases. That is, the gas turbines do not have fast responses within 5 minutes which calls to other flexibility option.

From Fig. 4, it is noted that the flexibility indices for gas turbines are significantly greater compared to those of steam turbines in the same time frame of 5 min and 15 min. Production units with minimum stable generation, high ramping rate, small minimum up and down time and low start-up costs are the most flexible.. These additional sources are flexibility options to what they possess as quick response. Then, as shown in the figure, the flexibility index of these options is 100%, which explains the almost instantaneous response of these energy sources. Hydraulic power stations are not mentioned in this scenario because of their reduced availability.

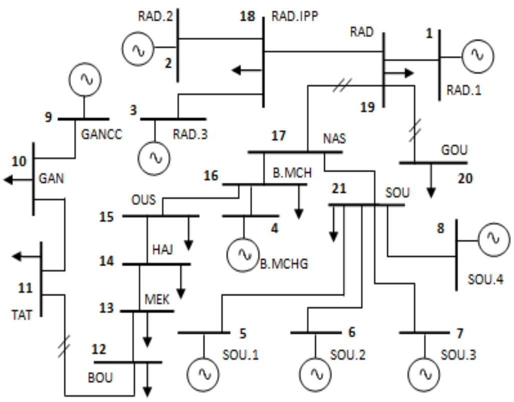


Fig. 2 Reduced 21-bus model of the Tunisian power system

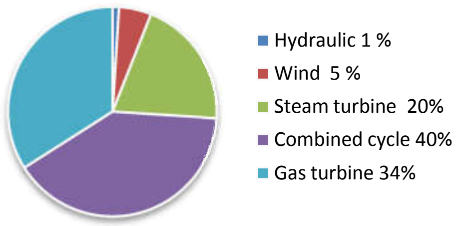


Fig. 3 Installed generation by generator type [8]

**Table 1.** Generators of the Tunisian electrical network

| Generator type | Bus No | Flex up (%) | Flex down (%) | Flex index (%) |
|---|---|---|---|---|
| Gas Turbine | 4 | 54 | 54 | 54 |
| | 2 | 61 | 84 | 45 |
| | 6 | 39.7 | 39.7 | 39.7 |
| | 7 | 50.7 | 75.7 | 99 |
| Steam Turbine | 1 | 34 | 33 | 33.6 |
| | 5 | 35 | 35 | 35 |
| | | 34 | 34 | 34 |
| Combined Cyle | 1 | 15 | 53 | 34 |
| | 5 | 22 | 30 | 26 |

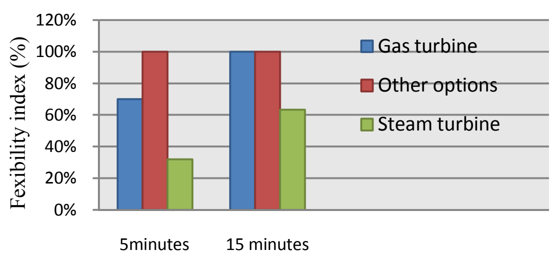


Fig. 4 Flexibility indicepes for differen types of power sources

## V. Flexibility Evaluation Incorporating Renewable

In this section, we present a methodology for determining the optimal generation mix to provide the flexibility required for accommodating a given amount of wind generation. The goal is to help in short-term operational decisions on how these renewable power plants are scheduled. The Unit commitment plan enforces the dynamic constraints, such as ramping rate and minimum up/down time, that drive the need for flexibility.

### *5.1 Maximum Wind Power and Reserve*

As wind power forecast is not accurate, the maximum wind power a generation scheduling can accept should be determined in order to adjust spinning reserve. In an interval, when the unit commitment does not meet the reserve demand, a new unit may start up or an old one shuts down to satisfy the constraints (4), (5) and (6).

### *5.2 Flexibility requirement for wind energy*

The target day is 16/06/2014, chosen based on the remarkable availability of wind and solar energies. Figure present the load of the target day. The day-ahead forecast can refined up to 15 minutes of forecast. In order to determine an optimal generation scheduling incorporating renewable energies, the working interval is divided into sub-interval to determine optimal generation mix for each interval. In this study, the total period used for measurements is divided into 12 time intervals of two hours as shown in Fig. 6. These intervals are characterized by the following data: demand, spinning reserves, wind and solar energy and total cost. Table 2 lists these data for each interval. These data will be used later in the power distribution algorithm. The total cost estimated by the dispatching is presented in Fig. 7. This cost gives a representation on the instantaneous cost of production in order to estimate the level of available fuel reserves. The production cost unit is the toe/MW.

To get a first approximation on the flexibility of the network and the ability to cope with the variability of renewable energies, we start by comparing the ramping rates of wind energy in this case with that of flexible conventional power plants.
Table 3 groups the highest rising and falling ramps of wind power production. In several cases, the wind ramp can be modified in ascending or descending directions: In order to avoid an acute ramp like the case of the ramp up 4 or the ramp down 3 in Fig. 5, the dispatching is either acts on the production parks by putting a park or two out of service, it is the effect of expansion, or it acts on the speed of the wind turbines by reducing the speed of the fins. This case is often produced in new technologies to reduce the ramp rate of the wind turbine.

After comparing the ramp rate of the wind turbine with the most flexible gas turbine ramps, it is evident that the lowest ramp of the gas turbines, which is equal to 1.1 MW / min, and greater than the largest ramp wind turbine that is worth 0.53MW / min. Then the Tunisian network benefits in terms of ramp rates of conventional power stations.

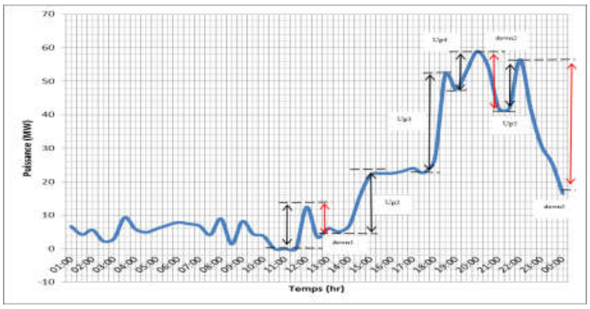

Fig. 5 Wind power generation on 16/06/2014

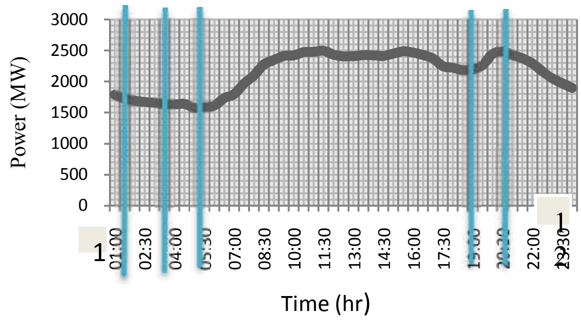


Fig. 6 Load curve on 16/06/2014

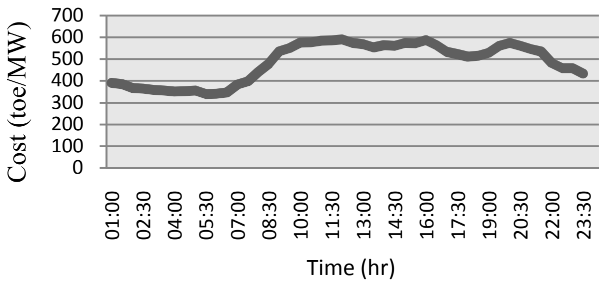


Fig. 7 Fuel cost on 16/06/2014

TABLE 2. DATA OF WORKING INTERVALS

| Interval | Demand (MW) | Spinning reserves (MW) | Solar //Wind | Estimated Cost (toe/MW) |
|---|---|---|---|---|
| [3:00 5:00] | 1574 | 384 | 0 // 3 | 355 |
| [5:00 7:00] | 1800 | 356 | 20 // 6 | 383 |
| [7:00 9:00] | 2300 | 275 | 78 // 7 | 536 |
| [9:00 11:00] | 2341 | 292 | 93 // 8 | 584 |
| [11:00 13:00] | 2345 | 339 | 99 // 0 | 568 |
| 13:00 15:00] | 2400 | 310 | 99 // 22 | 574 |
| [15:00 17:00] | 2420 | 260 | 93 // 37 | 533 |
| [17:00 19:00] | 2412 | 428 | 77 // 48 | 528 |
| [19:00 21:00] | 2423 | 257 | 30 // 42 | 546 |
| [21:00 23:00] | 2048 | 141 | 0 // 42 | 458 |

TABLE 3. RAMP-UP AND RAMP-DOWN RATED OF THE WIND POWER

| Ramp-up Rate (MW/min) | Ramp-down rate (MW/min) |
|---|---|
| Rampup1 = 12/30 = 0.4 | Rampdown1 = 20/75 = 0.26 |
| Rampup2 = 18/75 = 0.24 | Rampdown2 = 12/37 = 0.24 |
| Rampup3 = 18/75 = 0.24 | Rampdown3 = 40/120 = 0.33 |
| Rampup4 = 12/30 = 0.4 | |
| Rampup5 = 16/30 = 0.53 | |

TABLE 4. OPERATIONAL COST ESTIMATION

| Study Interval | Generation mix | Total Cost (toe/MW) |
|---|---|---|
| 15:00 -17:00 | 8 TG | 316.035 |
| | 3 TG | 417.78 |
| | 1 CC + 2 GT | 393.822 |
| | 4 GT | 372.627 |

In terms of operational cost, Table 4 presents the costs for different generation mix scenarios during the studied interval. Comparing the results, we note thatt the scenario that optimizes the distribution with 8 gas turbines is less costly than the scenario with a combined cycle and two gas turbines. From a global perspective, the combined cycle is the cheapest in production, but during the distribution the cost of the scenario comprising the combined cycle may not be the most profitable.

## VI. CONCLUSION

This paper presented a study on flexibility of the Tunisian power system for incorporating an increased share of variable renewable energy. The purpose is to assess the need for additional flexibility requirements associated with the generation scheduling domain, which is mainly relevant to the hourly variation and uncertainty of renewable power output.

Flexibility was estimated based on a normalized flexibility index is used to estimate the flexibility level of single units and indicate their contribution to the whole system's flexibility. An interval-based generation scheduling is proposed based on a unit commitment algorithm. The study treated the case of Tunisia, as an example of a system with ambitious renewable share targets.

The methodology presented aims at determining the optimal generation mix to provide the flexibility required for accommodating a given amount of wind generation.

- Incorporating variable renewable power plants requires short-term operational decisions on how these plants are scheduled.
- The reduction in fuel cost by wind integration is partly offset by the cost of additional flexibility services involved at the same time.

## VII. ACKNOWLEDGEMENTS

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