Conventional Power Plants to TSO Frequency Containment Reserves – A Competitive Analysis for Virtual Power Plant's Role

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Abstract—**Frequency regulation is one of the basic objectives in ancillary market, which involves different stages and multiple participants. There exists different techniques for this service, where the points of demarcation are the time of service, and the regulatory requirements. The paper discusses primary frequency regulation, w.r.t Italian regulations, which is provided by conventional power plants upon TSO requests. The paper demonstrates conventional technique with its limitations, and proposes use of Virtual Power Plant (VPP) for the service provision. Storage and renewables techniques are compared under VPP context, and the use of storage is motivated. Finally, technical and economic comparison amongst potential storage techniques is done.**

Keywords—Frequency regulation; VPP; power plants; TSO; storage system

I. INTRODUCTION

Intermittencies in power grid requires further flexibility in ancillary market [1]. Two major ancillary services are the voltage and frequency control as in [2], for which real power and reactive power are the control parameters at point of transmission. The common approach is to keep reserves for the services; specifically real power reserves for frequency regulation [3-4]. These reserves vary in terms of regulations, timings requirements, and market participant.

From [5-6], there are three types of frequency reserves: Frequency Containment Reserves (FCR), Frequency Restoration Reserves (FRR) in automatic (secondary) and manual (tertiary) modes, and Replacement Reserves (RR). TSO, in general (excluding some European countries), remunerates the providers for FCR with a 30 seconds activation time [7-8]. The real power reserves that are used for FCR need to be very fast in response, and thus the participants for this service are bound to ensure the use of relevant technologies only [9]. Due to these characteristics requirements, battery energy storage is thus a literature mostly discussed solution as in [10].

The secondary reserves have a time limit of 7.5 minutes with a centralized control from TSO as in [11]. Different TSO of different countries may have different time limits, and different remuneration strategies. In the context of this paper, Italy is used as the reference country, and the primary reserves are only discussed. For Italian system, FCR has to be sustained for 30 seconds, and secondary reserves within 200 seconds. However, with the large frequency deviations, FCR has to arrive the settling frequency within 10 seconds [12]. With the new service providers in the market, another important service is Fast Frequency Response (FFR) for which TSO remunerates for restoration within 2 seconds [13]. Nadir frequency is assumed to be 100 mHz in the paper (0.2% with reference to 50 Hz), as a pessimistic bound for further analysis [14].

The next section II follows the details of how the service is provided by conventional power plants. The droop control system is implemented in Simulink, using modified IEEE 9 bus system. Two scenarios are investigated: one is the conventional FCR, while other is the FCR with deadline extension. For both scenarios, some test cases are simulated to analyze settling frequency, time of service, and duration of provided service. Section III further elaborates the concept of FCR to FFR, emphasizing on VPP concept with potential comparison amongst the options of storage and renewables. It further compares the different storage options using ES-Select tool. Section IV analyzes the potential use of proposed VPP, while section V concludes the paper.

II. CONVENTIONAL FCR TECHNIQUE – DESCRIPTION, DEMONSTRATION, & LIMITATIONS

First, Primary frequency control is provided by governor control at turbine, where the frequency is dependent on rotor angular speed. The details are provided in [15], with the equivalent representation of control in Figure 1, with the backward loop of droop control only, adapted from [15]. All values of turbine time constant, governor time constant, and inertia constant H [16] are taken from [15].

The compensation factor is deduced from [17], which occurs from the fact that the frequency variations are high enough, and thus the swing equation mechanical and electrical powers do not void each other. The model for this compensation power is, from [17], introduces a gain factor K incorporating the frequency changes and the dead-band. The modified form for the control is shown in Figure 1 with the gain factor loop. From [17], large dead-band is used to reduce procurement cost, following all the requirements of nadir frequency and FCR timings (settling time, and restoration
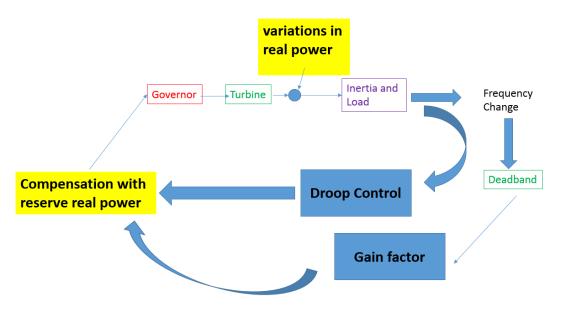
Fig. 1. Primary frequency control conventional technique – Conventional & Modified ([17])

time). Next step describes the test case that is used for the analysis. Consider the component model of IEEE 9 bus transmission system, as shown in Figure 2 [18-19]. For the sake of analysis, the transmission line (inductive and capacitive effects) and transmission impedances are ignored. In addition, generator 1 is supposed to supply representative loads A, B, and C only. In Italy, there is one area system concept, and thus the other generators are supposed to operate at same frequency (neglected in analysis here). For the rated power, the system is operated at a rated frequency. In other words, the frequency change is zero when there is no variation at the loads. Then, the load is varied from 1% to 10% of rated power (with step size of 1%), and the frequency change is observed. The point of disruption is noted, at that particular load level. The gain factor is applied with the real power reserves to adjust the frequency change within the required dead-band [17]. The time for the service is noted. The system is implemented in MATLAB/Simulink, with Governor time constant = 0.11 seconds, Turbine time constant = 0.40 seconds, Droop = 6%, extended dead-band = 80mHz,

All loads have 100 MW rated power. The results are presented in Table I. Positive load change means reduction in demand, while negative load change indicates the distributed generation or co-generation. For the 10% change in load, the frequency deviation is 63 mHz. The gain factor is set to 10 in all cases. With the case of loss of load, the frequency does not come to settling within 10 seconds, as in Figure 3. With the co-generation of 50%, the frequency deviation violates the dead-band. Deviation is reduced to 22 mHz, and with the gain factor of 5, the frequency deviation is reduced to 27.5 mHz. The problem in both cases is the increase in the time for service provision (i.e. the frequency settling time). The compensation is provided through primary real power reserves, and the conventional technique is the synchronous generators for the

provision. Table I shows all the cases for the provision of service within the dead-band.
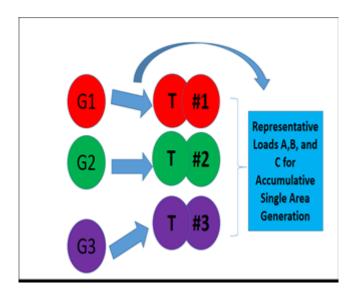

Fig. 2. IEEE 9-bus component selection [18-19]

III. PROPOSED VPP TECHNIQUE FOR FCR SERVICE: STORAGE VS RENEWABLES

In order to create market for FFR, the primary response has to be fast enough. This requires techniques with fast response for better compensation of real power reserves. The compensation can be provided through conventional, and VPP based techniques; and the analysis is shown in Table II [16]

[20]. The new actors employ inverter-based techniques for the service with emphasis on response to service request, service restoration time, and economics for low/high provision. The table shows that storage system is best suited in terms of better flexibility, adequacy, and response time. Next step is to compare potential storage technologies for the frequency service.

TABLE I. ANALYSIS RESULTS

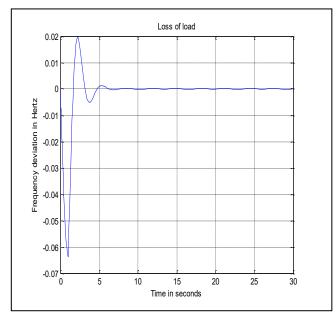| Percentage change in load (%)	Frequency change within deadband?	Time of service - seconds
+10	Yes- 63 mHz	8
Loss of Load	Yes (but do not settle within 10 seconds)	Failure (Figure 3)
-10	Yes-65 mHz	6
-50	No-81 mHz	Failure
-48	Yes-79.69 mHz(but do not settle within 10 seconds)	Failure
-49	No-80.36 mHz	Failure
-47	Yes- 79.71 mHz	7 (Figure 4)

Fig. 3. Frequency behavior with loss of load

Literature suggests a variety of electrical storage options in various forms, and the distinctions are made according to applications. For the provision of FFR, the parameters of interest include response time, discharge duration, rated power, and the maturity level of technology. From a long list of potential technologies, four are chosen on technical grounds and for further economic analysis. The choice covers all

maturity levels of technology, and suitable parameters range for this application [21].

The first one is flywheel, with response time in seconds; up to 15 minutes discharge duration, and commercial availability. Next commercial solution is advanced Li-ion with better response time and discharge duration. Lead acid is chosen as mature, and flow batteries mechanism is considered as developing option. The selection is based on analysis in [21]. Further selection amongst these four depends on capital/operating costs, and the procurement application. Next section is dedicated to economic analysis amongst these four technologies, and then to analyze the performance of the selected one w.r.t base conventional technique in section II.
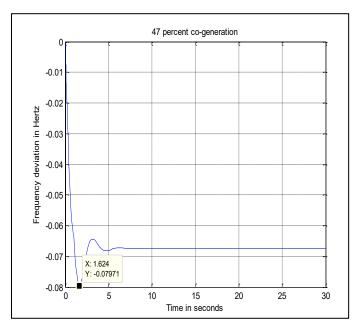

Fig. 4. Frequency behavior with 47% co-generation

TABLE II. POTENTIAL SERVICE PROVIDERS

Technique Name	Key points
Synchronous Generator	High amount of provision at high costs. High activation time of 5-6 seconds. Provision can be as long as the machine is in operation.
VPP based battery storage system	High amount of provision with better flexibility than SG. Only point is absence of grid inertia Faster than SG; battery discharges at a faster rate. 200 m-sec response time. Low activation time [20]
VPP based wind farm	High (but investments are required to build doubly fed induction generators plant). Grid inertia provided by supplementary control loop Activation in 12 seconds Intermittent without storage Suitable for small scale [16]

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IV. ANALYSIS FOR PROPOSED VPP WITH POTENTIAL STORAGE OPTIONS FOR FCR

These four storage technologies are economically compared using ES-Select tool [22]. Investment cost VS discharge duration analysis is presented in Figure 5. For each of the four technologies, the discharge duration and the investment costs are compared at rated efficiency. Three rated efficiency values are used: 50%, 75%, and 80% respectively. However, in order to create a better visualization with the technical analysis in previous section, the graph displaying efficiency-discharge duration is shown in Figure 6. From the analysis of Figures 5-6, it is visible that flow batteries require the least capital investment and provide the best discharge duration. However, the technology is not mature enough and the efficiency is the least amongst the selected options. Lithium-ion is the average in capital costs and discharge duration, but it provides the best efficiency with the commercial level maturity. Lead acid is the most expensive investment, but is better in energy efficiency and maturity level. Flywheel is an emerging technique with limitations on discharge duration, so it can only serve a limited period. VPP integrated model is shown in Figure 7.
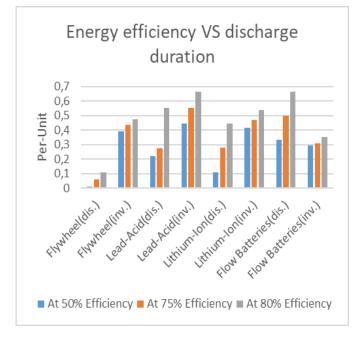

Fig. 5. Discharge duration VS investment for battery options

Next step is to perform the techno-economic analysis on a single scale, to decide the best regions of operation for each selected technology. The analysis is performed in Per Unit (PU), with the following base values: 5000$ for investment, 5 hours for discharge duration, and 100% for efficiency. The rated power is assumed 100 MW to comply with base case, and the results are shown in Figure 8. The results can be analyzed starting from efficiency, which can be divided into two zones: High efficiency zone, and Reduced efficiency zone. For the high efficiency zone, the competition is amongst flywheel, lithium-ion, and lead-acid. Within this zone, the most expensive option is lead-acid, but with the best discharge duration. In order to reduce the investments, there is a point of comparison amongst flywheel and Lithium-ion. For a given

cost, flywheel provides less discharge duration than Lithium-ion. Therefore, flywheel is discraded from this zone. For the reduced efficiency zone, flow battery is the best option with the best discharge duration, and least investment. This leads to three competitors, i.e. lead-acid, lithium-ion, and flow dabbteries amongst two different application zones. The analysis is shown in Table III.

For FFR, the requirement is high efficiency, so the comparison remains amongst lead-acid and lithium-ion. For the service provision, aggregation for both these technologies is used. Next step is to compare the performance of aggregated storage option with three cases: mixed aggregation, 60-40% aggregation, and 70-30% aggregation mix. The results are shown in Figure 8, which shows that the aggregation, as a package, is always better than the base cases. TSO can request the service in any such forms, it can be the fast service for which efficiency is considered in Figure 9. For long service duration, discharge duration is given importance, and for reduced costs (at high flexibility), aggregation trade-off can be visualized. These aggregation criterion are representative of the technology, and the use of service. It also depends upon the specific service requirement from TSO.
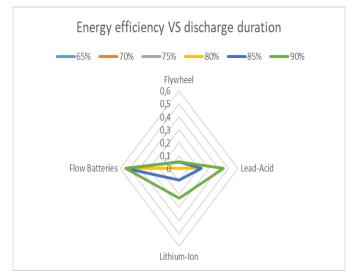

Fig. 6. Energy efficiency VS discharge duration for battery options

TABLE III. APPLICATION ZONES VS POTENTIAL PROVIDER

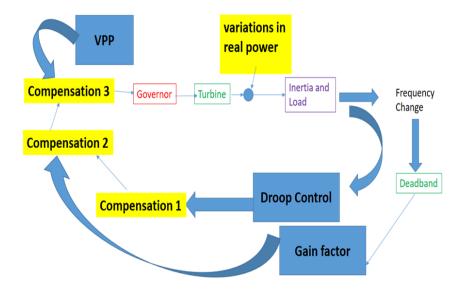| Zone of Operation	Prioritized Options	Merits
High Efficiency	Lead-acid and Lithium-ion	Trade-off amongst costs, and discharge duration, with best efficiency
Reduced Efficiency	Flow batteries	Best discharge duration, and least cost requirements, but with compromised efficiency

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Fig. 7.   Frequency control integrated technique – with VPP ([17])

The idea of Virtual Power Plant here is to involve the different market participants, and storage is the current market trend. However, the integration of VPP in the current market scenario will impose regulatory, technical, interoperability, and privacy challenges. These peculiarities of VPP involves the identification of new possible market schemes, which comply with the requirements of integration.
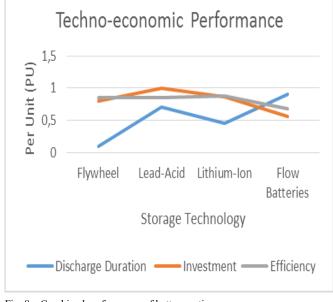

Fig. 8.   Combined performance of battery options

V.   CONCLUSION

The paper demonstrates FCR with conventional technique and the potential use of VPP for FFR. Storage technique is

emphasized, and different storage options are compared for the service. The results demonstrate that the technical and economic feasibility of FFR has trade-off amongst the VPP based strategies, and it is a good rationale to aggregate them as a future potential solution.

Future work involves secondary and tertiary frequency reserves on top of FCR service, and the extension of VPP involvement towards other ancillary services, example reactive power for voltage support. Another possible extension is the real-time validation of TSO based procurement for the service.
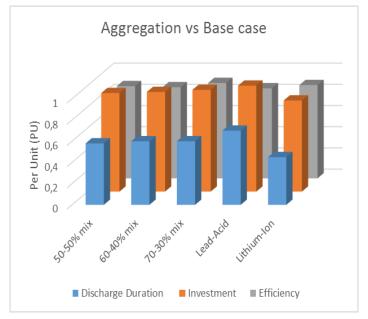

Fig. 9.   Aggregated performance of battery options

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