TRANSNATIONAL ACCESS
Technical Report

D-POVERED: Dynamic Performance assessment Of Variable Electricity Renewable-based generation units in Distribution systems

Ali Mehrizi-Sani; Virginia Tech; United States
mehrizi@vt.edu

1 INTRODUCTION

Power systems have been historically expected to operate in a plug-and-play fashion. While in the conventional power system, because of its ample inertia and large generators, frequent small changes in the system may not pose any significant challenge. Moving forward, as (i) the system gets smaller (microgrids) or (ii) the resources become more sensitive to changes (power electronics--based inverters), the need to ensure that the system dynamics are regulated increases to avoid apparatus malfunction, dynamic response challenges, and protection issues. Set point automatic adjustment with correction enabled (SPAACE) is an add-on strategy to improve the performance of an existing controller when the controller itself is black boxed---a common scenario with inverters associated with utility-installed renewable systems. This work implements a smooth variant of SPAACE in an experimental test bed to evaluate the performance of a proposed linear prediction strategy in several scenarios. This new strategy allows for simpler and faster implementation of SPAACE in practical systems.

This project was very successful and led to significant new synergies between the Virginia Tech and University of Strathclyde partners. Consequently, the work performed under this project go significantly beyond the work proposed in our original proposal. For example, we have already submitted four papers, we are working on a larger proposal to be jointly submitted to EPSRC (UK) and NSF (US), and a student research visit program. Both parties plan to continue their collaboration, initially made possible through this grant. Our objectives in this project included the following:

- Implementation and performance evaluation of a new prediction strategy based on linear formulation to improve the performance of SSPAACE.
- Evaluation of the performance of SSPAACE in an experimental test bed with respect to two different prediction strategies in several scenarios.
- Establishing the practical feasibility and robustness of SPAACE utilizing a high fidelity hardware-in-the-loop systems level test bed.
- Evaluating the impact variations in parameters of SPAACE, e.g., predictors, implementations (within and outwith the DER inherent controller), expected modes of operation and subject to a selected range of day to day operational scenarios.
- (ADDED DURING THE PROJECT) Study and proposing an augmented load frequency control (ALFC), enabled by augmenting the conventional load frequency control with a modulated power balance control loop (MPBCL). Therefore, ALFC ensures (i) locationally

targeted frequency response, (ii) tuning-free operation, and (iii) enhanced temporal and dynamic frequency response in the future renewables-rich power system.

- Proposing an approach to ensure dynamically robust set point regulation as a virtual power plant.

2 SETUP

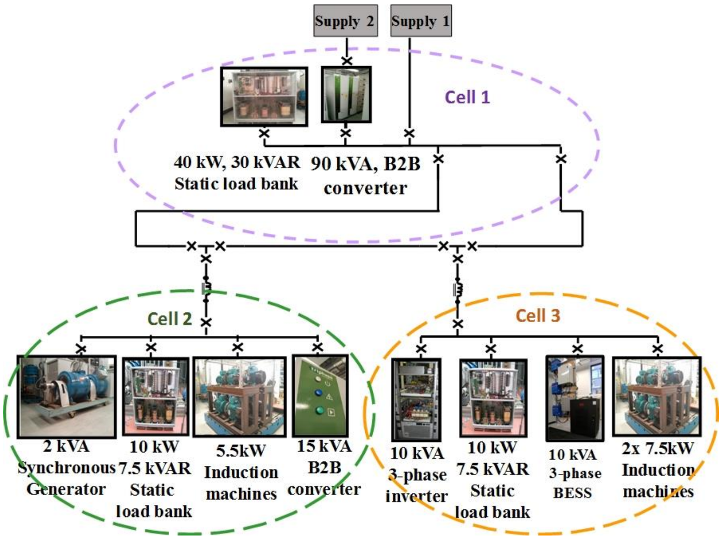

Figure 1. Schematic diagram of the test system setup.

The performance evaluation of SSPAACE with lead compensator prediction and proposed linear prediction strategies is undertaken at the University of Strathclyde's Dynamic Power Systems Laboratory (DPSL), a 115 kVA, low voltage (400 V) three-phase experimental facility. A simplified one-line diagram of the power network at DPSL is shown in Fig. 1. A combination of conventional and non-synchronous generation as well as static and dynamic loads allow for representation of land-marine-aero electrical power systems at scale complemented by a NovaCor digital real-time simulator (DRTS) from RTDS Technologies for controller and power hardware-in-the-loop experiments. Fig. 2 shows the test configuration utilized for performance evaluation studies in this paper. A simple network, comprising a synchronous generator (SG) and an on load tap changer (OLTC) simulated within RTDS, provides the reference voltage for reproduction by the 90 kVA back-to-back (B2B) power interface. The 15 kVA B2B converter is chosen as the distributed energy resource (DER), emulating a power electronics--interfaced energy storage system. A 7.5 kVA induction machine and two 12 kVA static load banks allow testing load switching transients.

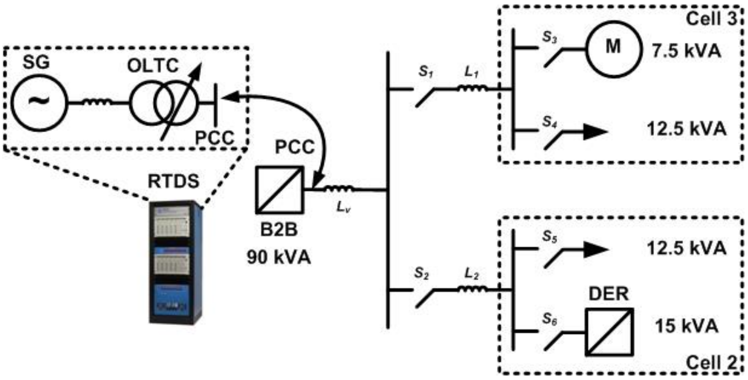

Figure 2. Test configuration based on the setup at the University of Strathclyde.

3 METHODOLOGY AND APPROACH

We have designed an autonomous, scalable strategy, called set point automatic adjustment with correction enabled (SPAACE) to improve the performance of an existing controller without requiring access to its internal structure. Ideally, SPAACE treats the system as a black box. However, a full black box approach is not realistically possible, and we will discuss how we will depart from this assumption.

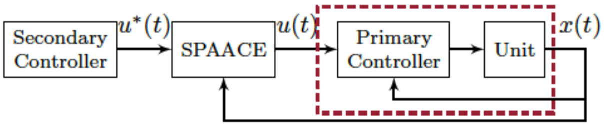

Figure 3. Overall structure of the SPAACE algorithm.

To discuss the basics of SPAACE, assume the set point *u(t)* is step changed from u_1 to u_2, where without loss of generality we assume $u_2 > u_1$. In response to this change, *x(t)* initially increases and may experience a large overshoot and/or a long settling time. Of course, this can be a characteristic of the controller, but alleviating this problem requires controller redesign. Instead, SPAACE can respond to this situation as follows. If it predicts that the overshoot of *x(t)* exceeds the maximum permissible value, it will issue a command to temporarily scale down *u(t)* from u_2 to $(1 - m)u_2$, where m is a design parameter. When the trend of *x(t)* indicates it will be within the acceptable region, SPAACE releases *u(t)* so that *x(t)* settles to u_2 (and tracks *u(t)* as intended). The manipulated response has a much smaller overshoot and a shorter settling time. A negative step change ($u_1 > u_2$) is dealt with similarly, but a scaled up set point of $(1 + m)u_2$ is used instead. Note that manipulating *u(t)* does not modify the internal dynamics of the system.

The success of SPAACE in improving the response characteristics depends on carefully determining the instants at which the reference set point *u(t)* is changed, i.e., the time the set point is scaled down (T_1) and the time the set point is restored (T_2). The problem of calculating these two instants can be posed either as an exhaustive search or as an optimization problem to minimize $\int_0^\infty (u^*(t) - x(t))^2\,dt$. However, deriving analytical expressions for T_1 and T_2 is of limited practical use as it requires the knowledge of system parameters a priori. To show feasibility of SPAACE, we have shown that T_1 and T_2 do exist for a second-order system. We have shown that choosing T_1 such that peak of the response equals x_2 and choosing T_2 to be the instant t_p that the peak occurs results in the optimal response that has zero overshoot and its settling time is t_p. In practice, the system is not linear, and even if a linearized model is used, its order will clearly be much higher than 2. Therefore, we will develop prediction mechanisms to forecast the behavior of the system response, based on which the instants for changing the set point will be determined. We will also dene a quantifiable metric to evaluate the quality of set point tracking. This metric should reflect both the magnitude and the duration of deviation of the response *x(t)* from the set point *u(t)*. One candidate metric is the accumulative error as defined by

$$\int_{t=t_0}^{t_f} \left(u^*(t) - x(t)\right)^2 dt, \qquad (1)$$

where t_0 is the time when the disturbance occurs, and t_f is when the response reaches the steady state. Other potential metrics that we will study include a combination of percent overshoot, settling time, and the absolute value of peak as well as the discrete-time equivalent of (1).

SPAACE and its different variations are implemented under varying operation scenarios in this work. Examples include a utility microgrid, a DC microgrid, virtual power plant, and load frequency control.

4 ACHIEVEMENTS

Our achievements under this project can be categorized as below:

- Design of an autonomous controller to operate under varying power system operational scenarios, including utility microgrids, DC microgrids, renewables integration, and load frequency control.
- Better understanding of implementation challenges related to experimental evaluation of the proposed controllers and different architectures.
- Synergies in collaboration between Virginia Tech and the University of Strathclyde leading to student visits, talks, and joint proposal submissions.
- Joint paper publications including 4 submissions for peer-reviewed venues and a few more planned.

Specifically, we have had the following technical achievements:

4.1 SPAACE as an Addon Controller

We have created an add-on function to improve the performance of existing controllers when the system characteristics changes and the controlled unit is sensitive to overvoltages and overcurrents. This add-on controller, referred to as SPAACE, uses prediction of the system response to modulate its set point to achieve the desired response trajectory. This work presents a smooth modulation strategy for SPAACE and discusses the performance of different prediction strategies, as validated based on a hardware test bed. Our extensive case studies show the superior performance of a simple, linear-based prediction law in appreciably improving the dynamic response characteristics, e.g., settling time, overshoot, and tracking error, of a DER unit interfaced by power electronics.

4.2 SPAACE for Load-Frequency Control

We have also proposed an ALFC approach and demonstrated its robustness to changes in system parameters. Two key features of the approach are (i) tuning-free operation under varying system conditions, and (ii) ease of integration and enhanced scalability given its architectural flexibility facilitating the move towards an inverter dominated grid.

4.3 Establishment of Experimental Implementation Best Practices

A high-fidelity hardware-in-the-loop experimental test bed has been utilized to prove the practical real-world feasibility of an add-on controller, SPAACE, designed to improve the performance of existing controllers in an inverter-dominated power system. The following observations are highlighted:

- The linear predictor is computationally most efficient with least time and space complexity. In addition, the time and space complexity of a linear predictor do not increase with an increase in prediction horizon.
- The choice of predictor only marginally impacts the dynamic performance and therefore, based on the computational performance evaluation, the use of a linear predictor is recommended. This is an application specific recommendation, however, the trade-off

between computational and dynamic performance should be assessed, specifically given the demonstrated close performance of linear and quadratic predictors.

- With a weak controller (in grid-connected mode) and a strong controller (in islanded mode), the incorporation of SPAACE leads to improvement in the dynamic properties (at least one of settling time, overshoot, and tracking error) of the response subject to the studied disturbances.
- The set of events chosen are non-exhaustive but sufficient for demonstration of the performance of the approach under a broad range of circumstances. However, given the versatility of its operation, improvement of dynamics under unknown system conditions can be expected.
- When SPAACE is implemented external to a primary controller, a slight deterioration in performance of SPAACE compared to its implementation within the primary controller is observed. This deterioration in performance is associated with the time delay of the implementation that highlights an important aspect of future work, i.e., to incorporate time delay within the design of the predictor.

4.4 SPAACE for Virtual Power Plants

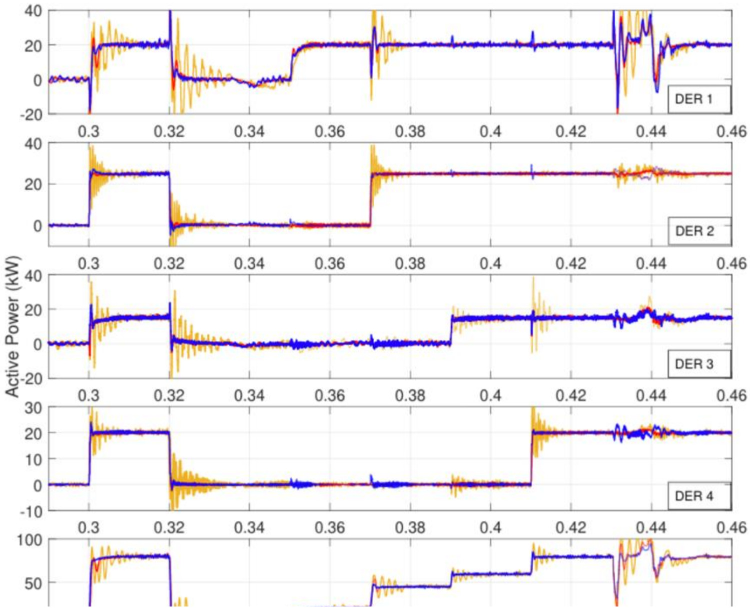

Figure 4. Example results pertaining to the improvement of the dynamic performance of a microgrid augmented with the proposed SPAACE algorithm.

We have also studied the performance a coordinated set point modulation (SPM) approach to enhance the cumulative dynamic response of distributed DERs participating in ancillary service provision at a chosen point of common coupling (PCC). The performance of the proposed approach is benchmarked against a decentralized approach and a conventional approach where no SPM is incorporated. It has been shown that both the decentralized approach and the proposed coordinated approach perform significantly better than the conventional approach. The decentralized approach improves the local response of the participating DER, however does not help the cumulative response at the PCC. The proposed approach in contrast improves the local dynamic response and the cumulative dynamic response at the PCC. The performance of the approach has been verified within a low voltage AC distribution network and a DC distribution network, demonstrating its flexibility for adoption within wider networks. The real-world applicability of the approach has further been demonstrated through a high fidelity power hardware-in-the-loop experimental validation. The proposed control will allow virtual power plants to ensure tighter regulation at PCC's of interest such as the distribution-transmission interface and to participate in markets with more stringent time and regulation requirements.

5 PUBLICATIONS

ACCEPTED OR PUBLISHED

1. M. H. Syed, E. Guillo-Sansano, A. Mehrizi-Sani, and G. M. Burt, “Prediction strategies for smooth set point modulation to improve sensitive DER response,” in IEEE PES General Meeting, Montreal, QC, Aug. 2020.

SUBMITTED PENDING REVIEW

2. M. H. Syed, E. Guillo-Sansano, A. Mehrizi-Sani, and G. M. Burt, “Facilitating the transition to an inverter-dominated power system: Experimental evaluation of an integrated predictive controller,” IEEE Access, Apr. 2020, submitted for review (first revision).
3. M. H. Syed, E. Guillo-Sansano, A. Mehrizi-Sani, and G. M. Burt, “Load frequency control in variable inertia systems: Architecturally flexible set point modulation,” IEEE Power Eng. Lett., Dec. 2019, submitted for review (PESL-00306-2019.R1).
4. M. H. Syed, E. Guillo-Sansano, D. Wang, A. Mehrizi-Sani, G. M. Burt, and Y. Xu, “Coordinated predictive control of distributed energy resources for dynamically robust regulation as a virtual power plant,” in IEEE Int. Conf. Ind. Inform. (INDIN), Guangzhou, China, Jul. 2020 (submitted for review).
5. A talk was planned at the University of Strathclyde in March 2020 but the trip was cancelled due to COVID-19. We hope to be able to reschedule this trip at a later time.