Positive Sequence and EMT Domain Modeling of Grid Forming Hybrid Plants for Transmission Studies

Brian Graham
Electric Power Research Institute (EPRI) Europe DAC,
Dublin, Ireland
bgraham@epri.com

Deepak Ramasubramanian
Electric Power Research Institute (EPRI),
Knoxville, TN
dramasubramanian@epri.com

Abstract — **Hybrid power plants (HPPs) are an emerging technology generally defined as multiple different generation and/or storage resources behind a single point of interconnection. This blend of technologies possesses several advantages over conventional generation, such as reducing curtailment of renewables sources, peak shaving, among other benefits. However, at present, HPPs are not currently allowed for in some jurisdictions in the world due to their novelty, and there is no unified definition of HPPs across jurisdictions, which makes it difficult for widespread integration.**

With many HPPs being inverter-based resources such as battery energy storage systems (BESS) with solar plants, it is important to verify the behaviour of such plants in the electromagnetic transient (EMT) domain. Further, it is important to understand the various services that such plants can provide to the network, and the different factors that may impact the provision of such services. With the increase of inverter-based resources (IBRs) in the network, it is also possible that soon, for few hours of the day, many power systems can be 100% fed from inverter-based generation. In this scenario, the performance of HPPs, and their potential grid forming capability is to be investigated.

This paper aims to address modelling challenges with HPPs in the positive sequence and EMT domains for issues such as stability, controller interaction, circulating AC current and demand response. The impact of HPPs on frequency stability and damping of power system oscillations will be shown. Further, the use of generic models to represent the behaviour of the hybrid plant is discussed.

Keywords – Hybrid power plant, positive sequence, EMT, stability, transmission planning.

I. Introduction

Large-scale renewable energy sources (RES) such as wind and solar are beginning to have a significant footprint on electricity production around the world. Countries such as Ireland and the UK have achieved annual RES penetrations of over 40% in the past (42% and 43% in 2020 respectively [1], [2]), dominated by wind energy, while California has achieved 94.5% instantaneous RES penetration, dominated by solar energy [3]. However, wide scale integration of inverter-based resources (IBRs) can have an impact on the stability of power systems, and they also do not generally have the capability to provide services such as demand response on their own.

Hybrid power plants (HPPs) have been used for some time as power sources for remote locations such as mines/isolated towns [4] and islands [5], [6], often diesel/gas generator combined with RES and/or storage. There are also numerous examples around the world of the addition of solar thermal systems aimed at supplementing heat generation in systems such as geothermal, coal, and gas [7]. The outcomes of these projects have been mixed, with some operating for 10+ years, while other plants have discontinued [8], [9]. Increasingly, HPPs have become options when connecting in large scale power plants into transmission systems. In the US, solar PV + BESS is a common configuration for new solar farms, as well as hybridizing existing solar PV plants, allowing the plant to participate in the ancillary services market, thus improving revenue and system stability. Furthermore, the practice of over-rating solar panels in a solar farm versus the rating of the inverter interfacing the farm and the power system (120 MW solar PV vs 100 MW inverter) means that hybridizing the solar PV plant with the addition of a BESS minimizes the clipping loss associated with over-rating the solar panels, improving energy yield. For countries such as Ireland and the UK, where RES is predominantly made up of wind, hybrid plants present a solution to the intermittency of wind. These could be combined with storage and/or gas generation to supplement wind, while also reducing curtailment events (12.1% of potential wind energy curtailed in Ireland in 2020 [16]).

This paper aims to address challenges in modelling HPPs in transmission studies and the impact of integrating grid forming HPPs into transmission systems in the positive sequence and EMT domains.

Section II and III deal with the benefits and challenges of HPPs. Section IV presents case studies conducted in the positive sequence RMS domain in DIgSILENT PowerFactory using generic WECC models of wind, solar, and BESS plants, and in the EMT domain in PSCAD. Section V concludes the paper and outlines future work.

II. Benefits of Hybrid Power Plants

A. Reduced Frequency of Curtailment Events

Curtailment is defined by CAISO as the reduction of output of a renewable resource below what it could have otherwise produced [10]. This can be due to:

- Economic – when the market finds a place for low/negative-priced energy.
- Self-scheduled – reduce generation from self-scheduled bids
- Exceptional dispatch – ISO orders generators to turn down output

A key constraint at present on some networks at present is the RES penetration limit, which would come under the exceptional dispatch heading mentioned above. The RES penetration limit may also be characterized under the term System Non-Synchronous Penetration (SNSP), which is the proportion of inverter-based resources (IBR), not including imports and exports, out of the total system generation. IBR that are naturally decoupled from the system by power electronics may be ordered to turn down its output in favour of a synchronous generation unit to ensure system stability.

While turning down the plant output is needed to do ensure system security, turning down the actual generation unit's output could be avoided by redirecting the power flow from the grid to a BESS, for example, allowing the plant operator to supply this zero-carbon energy at a later stage.

Curtailment of generation can also happen in the more standard case where generation exceeds demand. Hydrogen generation could particularly be a good long-term option for this scenario, as BESS can only absorb a finite amount of energy, while hydrogen can be continually produced provided water is available.

1) California

Curtailment of RES in California reached over 5% in 2020, with over 12% of all solar production curtailed during the month of April, amounting to over 300 GWh of energy production, seen in Figure 1 [11]. The amount of curtailed energy has significantly increased year-on-year, with a particularly high amount of curtailment during the summer months due to the high solar penetration in the California grid [12]. CAISO also specify solutions that have the potential to reduce curtailment, with storage being regarded as a key factor in the solution. With storage integrated into HPPs, electrically close to the generating unit, this represents the most efficient method of storage as it eliminates a certain amount of transmission and transformer losses.

2) Ireland

At present, Ireland's grid can handle an SNSP up to 70%, with a plan by EirGrid to increase this to over 90% by 2030 through the DS3 program [13], [14]. In instances where the SNSP limit is reached, power from generating units that would normally be switched off could be redirected to storage units or to hydrogen production, mitigating some of the losses that would be incurred if the plant were to be switched off.

Furthermore, it is worth noting that in Ireland, for example, that the amount of RES generation installed in the system will far surpass the maximum daily peak of under 7 GW, with figures of 30 GW of floating offshore wind alone being mentioned in MaREI's EirWind report [15] to be in place by 2050, with EirGrid also suggesting up to 15 GW of RES being connected into the grid by 2030 [13]. Curtailment of these resources while they may be available will represent poor financial return for plant operators, which could be alleviated somewhat by integrating BESS and/or hydrogen generation into the plant.

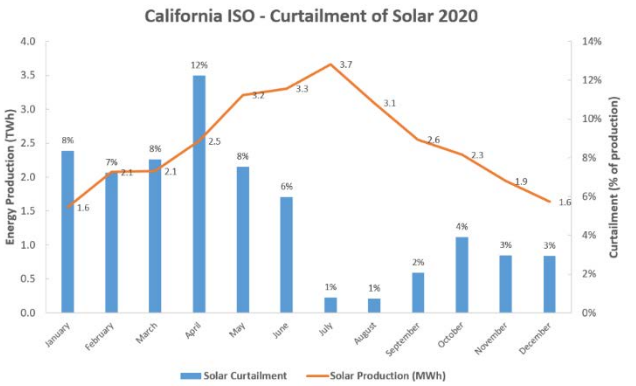

Figure 1
Solar Curtailment in California, 2020

According to the All-Island Quarterly Wind Dispatch Down Report 2020, released by EirGrid/SONI in Q4 2020, the proportion of wind energy curtailed increased from 7.7% in 2019 to 12.1% in 2020 [16]. This is partly due to the RES penetration limit up the start of 2021 constraining the Irish network to 65% SNSP. A trial conducted as part of the DS3 program in Q1 2021 aimed to increase this to 70%, and thus far EirGrid has successfully operated the network at this level of SNSP for a sustained period [14].

While instantaneous SNSP of 70% and above into a network has been done in systems such as California, there are challenges faced by Ireland due to it being an island system with no coupled interconnection (EWIC and Moyle totalling 1 GW, both DC) including frequency, transient, and voltage stability, as well as system strength/fault current. By contrast, California has significant coupled interconnection with nearby jurisdictions, meaning that Ireland's concerns relating to high SNSP are lessened. At present, these curtailment events require some wind farm operators to cease supplying power to the network, and thus represent a loss to the operator while being curtailed. In a particular week in January 2021, EirGrid was forced to curtail at 15.4% of available wind power over a 6-day period. A HPP would mean that, during the curtailment event, the power generated by the wind farms could be redirected to an energy storage device (BESS, etc.) or used to power an electrolyzer and produce green hydrogen, maximizing the amount of zero-carbon power usage.

Into the future, the aims set out in a number of documents such as the EirWind project [15] and the Building Offshore Wind: 70 by 30 Implementation Plan by the Irish Wind Energy Association [17] is the aim of building 30 GW of floating offshore wind in Ireland by 2050. With the highest ever system demand being less than 7 GW as of March 2021 [18], this would represent an abundance of wind energy that will need to be used in some way. Interconnection to the UK and the rest of Europe will help with this, but HPPs would guarantee the operator could use at least some of this energy internally in the HPP and not have to depend on factors outside of their control as much to keep their power plants generating.

B. Peak Shaving

With the integration of energy storage, particularly BESS, this means that excess energy can be stored for a later point in time. When demand is high, this stored energy can be released to the network, reducing the need for external plants to ramp up their generation, which is known as peak shaving. This leads to an overall flattening of the typical daily energy demand curve, which means the infeed units in the networks are not as stressed in terms of meeting the ramping demands as well as overall generation capacity and securing for an outage.

C. Isolated Networks

Hybrid plants also are an excellent method of reliable energy supply with RES penetration for an isolated network, using intermittent wind and solar generation, while also guaranteeing security of power supply by integrating wind and solar with technologies such as battery storage and gas fired generation, such as Agnew Renewable Energy Microgrid in Western Australia.

D. Improved Plant Capacity Factor

The intermittent nature of RES generation must be considered when integrating RES into a power system. Capacity factors for onshore wind and solar PV are generally the lowest of the capacity factors out of the more widely used generation types, and while offshore wind can have higher capacity factors, it is still usually lower than that of gas and coal [19]. However, as is illustrated in [20] and [21], the potential of PV power and capacity factor of wind power around the world are opposite of each other, with the windiest regions generally being close to the North/South Poles, while the highest PV power potential is naturally close to the equator. This complementary relationship of solar PV and wind power means there is potential to combine these in a HPP to yield a higher capacity factor, thus achieving a lower levelized cost of energy (LCOE), among other benefits associated with increased RES penetration. Further complementary relationships can be seen with the combination of geothermal and solar PV, as will be discussed with Stillwater GeoSolar Hybrid Plant in Section III.E.2).

E. Cost Savings and Additional Revenue Opportunities

HPPs represent an opportunity for plant operators to diversify and improve revenue streams for the plant.

1) Construction Cost Savings

A study into the costs of hybrid plants versus separate equivalent power plants in California and Texas found that the construction of a HPP instead of separate standalone wind/solar PV plants reduced the cost of the development by up to 10.9% [22]. This is likely due to the reduction in associated power electronics, transformers, as well as the process of gaining interconnection into the transmission system. However, cost reduction in comparison to stand-alone plants could be as low as 1.4%, in the case of stand-alone wind and battery plants vs. a hybridized plant of the two, which may not justify the hybridization of the development. This implies that a regional-based cost analysis would need to be done to adequately investigate whether hybridization is justified.

2) Curtailment of RES

At present, the curtailment of RES represents a loss for the plant operator, as the power plant cannot supply power to the network to its maximum capacity. Hybridizing these plants with electrolyzers, BESS, or other storage systems can help increase revenue for the plant operator.

3) Inverter Clipping

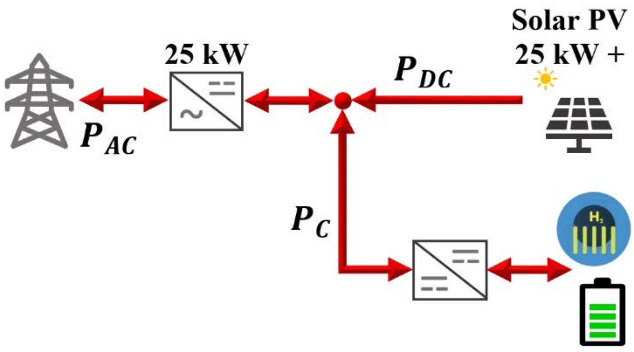

Figure 2
Inverter Clipping of Solar PV Output, Clipped Power Redirected to Storage/P2X

It is also common practice, due to the low solar PV panel cost compared to the grid inverter cost, for developers to install surplus solar PV panels with a total output power rating higher than that of the grid inverter, such as in Figure 2. This clipped power can then be redirected to a storage device, which can then be used for demand response or for load levelling.

4) Energy Storage

HPPs incorporating energy storage can yield revenue from various sources including:

- Hydrogen production to fuel industries such as transport and heat.
- Redirection of clipped power to storage to release during the evening peak hours when energy prices rise.
- Participation in ancillary services such as demand response, frequency/voltage regulation, among others, which will be discussed further in the next section.
- Storage of energy during curtailment events and releasing this energy at a later stage when energy prices increase.

5) Improved Market Participation

The addition of battery storage can allow the HPP operator to participate in ancillary service markets such as voltage control, blackstart, and frequency response, along with oscillation damping should the HPP operator decide to install a Power Oscillation Damper (POD) controller along with the battery, improving the stability of the grid by reducing power oscillation magnitudes and decay times. Furthermore, HPPs may offer an improved performance when participating in day-ahead markets, particularly with wind-plus-storage HPPs (as solar is more predictable), by reducing or removing the difference between the actual generation of wind generation units and the forecasted generation. This, as well as improving the reliability of wind plants, will reduce forecasting error penalties incurred on the wind plant operator. Various optimization strategies are discussed and one proposed in [23], seeking to either maximize plant revenue or reduce the variability of the plant output. The algorithm proposed in [23] maximizes plant revenue, with simulation results indicating an increase in revenue by over 10% compared to the operation of the wind plant without a battery. Other algorithms such as [24] have been proposed, but may not be practical, as they involve the full charge/discharge cycling of the battery, which will reduce the capacity and shorten the lifespan of the battery quicker than more shallow charge/discharge patterns.

III. Challenges in the Control of HPPs

A. Forecasting

Accurate forecasting for HPPs incorporating all technologies (wind, solar, etc.) present in the plant would be necessary, including when BESS may need to be charged. Inaccurate forecasting can incur penalties on the plant operator [25], so accurately forecasting each of the resources in combination and correlation with each other is important. Furthermore, utilities such as CAISO require the HPP plant owner to provide the forecasts for their plant, unlike other RES power plants, where the forecast is provided by CAISO [26]. Incorporating BESS to reduce discrepancies between the forecast and actual generation of the plant could alleviate some of these concerns, although is not a direct replacement to accurate forecasts.

B. Interconnection

Processes for facilitating the installation of HPPs should be developed due to their unique flexible nature. In instances where a BESS is included in the HPP, interconnection of these plants to the network can be facilitated at a lower power rating than the overall rating of the plant. For example, a HPP consisting of a 30 MW wind farm, a 20 MW solar farm and a 20 MW BESS can be connected into the system at 50 MW rather than 70 MW, which can avoid congestion issues. Similarly, adding 50 MW of BESS to a 100 MW solar plant will not cause issues to the system in the area, provided the plant operator does not supply more than 100 MW at any given time, unless previously agreed upon from the perspective of temporarily providing ancillary services. This is known at Net Zero Interconnection within MISO [27]. The upside of this for the TSO is that no new congestion issues occur, and no system upgrades may need to be implemented to facilitate this development, while the plant operator benefits from an increased return by storing excess power (from clipping, curtailment, etc.) and giving this back to the grid during periods of low-RES generation. The Federal Energy Regulatory Commission (FERC) Order 845 has facilitated this in the US [28].

C. Telemetry

Depending on how the plant is accounted for by the system operator (as multiple resources or a single aggregated resource), there may be a need for telemetry on each of the units, rather than one for the entire power plant. CAISO and NYISO require each resource to be telemetered, while PJM require metering at the point of interconnection of the plant. It may also be necessary to specify in scheduling whether the BESS is available, as the plant will not be capable of being a power sink when this is offline.

D. Managing SOC (HPPs with BESS)

Under some utilities (CAISO, MISO, ISO-NE), plant operators are expected to manage the SOC of their energy storage themselves. Additional data may need to be submitted to certify availability to ensure the dispatch schedule can be met.

E. HPPs around the World

1) Martin Next Generation Solar Energy Center, FL

A 75 MW solar thermal installation at Martin Next Generation Solar Energy Center was the first hybrid solar facility to combine solar thermal with a combined cycle natural gas plant [29]. It is also worth noting that the installation of the solar thermal array yielded an approximately 20% lower financial cost when compared to a similar stand-alone solar plant, due to the existing electrical infrastructure in the plant. The solar thermal power acts by replacing the need to burn natural gas to power the generators, rather than boosting the output power of the plant. The project was expected to yield approximately 155 GWh per annum, but in the years 2011-2020, the highest annual power generation attributed to the solar thermal array was just over 124 GWh in 2014, with just 30 GWh in 2020 [30].

2) Stillwater GeoSolar Hybrid Plant, NV

The power plant at Stillwater integrates 33 MW of geothermal power, 26.4 MW of solar PV and 2 MW of solar thermal energy, which is the first of its kind [31]. The solar PV and solar thermal panels were installed in 2015 to supplement the geothermal generation unit, and it is clear from the images seen in [32] that due to the seasonal aspects of both geothermal and solar generation, which are opposite each other, that the two generation sources complement each other, and combined can offer steady generation annually. This additional installation is expected to extend the life of the geothermal reservoir and are responsible for cutting CO_2 emissions by 28,000 tons per annum, generating 40 GWh annually [33].

3) Permian Energy Center, TX

The Permian Energy Center combines 420 MW of solar PV, made up of 1.3 million solar panels, and 40 MW (40 MWh) of battery storage, located in Andrews County, Texas [34]. The addition of the battery storage, with an hour's capacity at full output power of 40 MW, implies that the operator may plan on participating in markets such as rapid frequency response, rather than bulk energy storage.

4) El Hierro, Canary Islands

The island of El Hierro, part of the Canary Islands, inaugurated the Gorona del Viento power plant, which consists of a 11.5 MW wind farm and 6 MW of pumped storage power [35]. With a peak demand for the island being around 7.5 MW, the El Hierro HPP can supply over 65% of the island's energy demand for the year. It is estimated that since it began operations, Gorona del Viento has saved more than 20,000 tons of diesel and avoided over 80,000 tons of CO_2 emissions.

5) Termosolar Borges, Spain

Termosolar Borges is a HPP combining solar power and biomass with an output of 22.5 MW [36]. The power plant, costing approximately €153 million in 2012, can produce electricity 24 hours a day, maximizing solar power during the day and supplementing this with biomass when solar generation drops. It is quoted to produce an estimated 98 GWh/year [37].

6) Bulgana, Australia

Bulgana Green Power Hub is a project based in the state of Victoria, Australia, consisting of a 194 MW wind farm with a 20 MW/34 MWh battery storage unit installed [38]. It

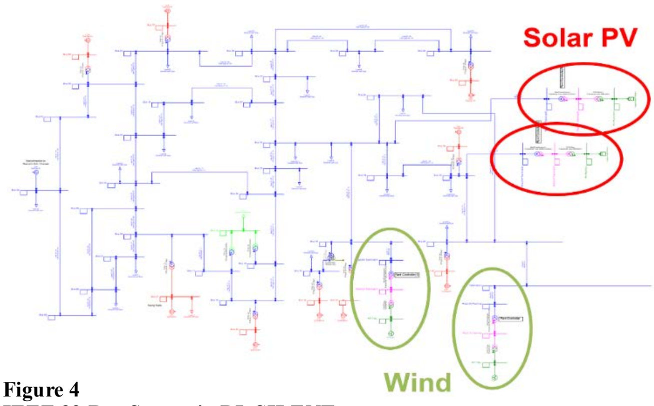

Figure 4
IEEE 39-Bus System in DIgSILENT PowerFactory

is estimated that it will supply approximately 750 GWh of clean electricity each year into the national grid [39].

7) Kogan Creek Solar Boost Project, Australia

The Solar Boost Project at Kogan Creek A power station in Queensland, Australia, was the plan to add a solar thermal generating unit on to the 750 MW coal-fired power plant [8]. This solar thermal addition, rated at 44 MW, would boost the output of the power station by evaporating and superheating boiler feedwater to power the power station's turbines. This would boost the power output of the plant, while burning the same amount of coal. Construction began in 2011, but the project was discontinued in 2016, citing contractual difficulties, as the solar thermal addition could not be completed without a significant amount of further investment, and there would never be any prospect of getting a return on that investment. A similar project at Liddell was constructed and put into service in 2013 [9]. This project cut CO_2 emissions by approximately 5,000 tons per annum, but the solar project was ceased in 2016, with the operator citing technical and contractual issues.

8) Agnew Renewable Energy Microgrid, Australia

A project centred on a gold mine in Western Australia is integrating an 18 MW wind farm, a 4 MW solar farm, and a 13 MW/4 MWh battery storage system with a 16 MW gas fired power station to fully serve the local mine [4]. Demand-side load management and predictive forecasting will be used to support the renewable generation. It was reported that the plant reached 85% renewable penetration in December 2020 [40].

IV. Case Studies

A. Positive Sequence RMS

To analyse the benefits and challenges of HPPs, several case studies were conducted in DIgSILENT PowerFactory using the IEEE 39 bus system. The base IEEE 39 bus system was altered by integrating 2 wind and 2 solar plant models. This required changing the MW dispatch of the existing generators in the network, as well as some loads, in the following manner:

- Synchronous generators (total decrease in dispatched power: 1461 MW)
  - G02: 520 MW to 244 MW (-276 MW)
  - G03: 650 MW to 600 MW (-50 MW)
  - G04: 632 MW to 600 MW (-32 MW)
  - G05: 508 MW to 150 MW (-358 MW)
  - G06: 650 MW to 250 MW (-400 MW)
  - G07: 560 MW to 425 MW (-135 MW)
  - G08: 540 MW to 490 MW (-50 MW)
  - G09: 830 MW to 720 MW (-110 MW)
  - G10: 250 MW to 200 MW (-50 MW)
- Loads (total increase in load: 2,943.5 MW)
  - Load 04: +200 MW
  - Load 08: +678 MW
  - Load 12: +142 MW
  - Load 16: -79 MW
  - Load 16(1): +250 MW
  - Load 23: +752.5 MW
  - Load 23(1): +1,000 MW
- RES integration
  - Solar PV: +1,600 MW (1x1,000 MW, 1x600 MW)
  - Wind: +2,900 MW (1x1,400 MW, 1x1,500 MW)

Given a system load of just over 9,000 MW, the SNSP of the network was 50%. An overview of the system with the placement of the RES plants is shown in Figure 3. The solar PV and wind plant models used were WECC generic models from the DIgSILENT Library. We modelled a generic HPP using a wind plant integrated with a BESS behind a single point of interconnection, as shown in Figure 4.

1) Generator Outage

In the case considered here, a generator outage is initiated at t=1s, amounting to a 250 MW outage. Shown in Figure 5 are the simulation results for 10 MWh batteries at different MVA ratings. Compared to the case where there is no BESS in the system, the addition of BESS has improved the frequency response of the network substantially. The droop gains for the plant controllers in the network were set quite aggressively to produce this frequency response, and so would need further study when integrating into a larger network to ensure stability.

These results display up to 77% improvement in frequency nadir for the 200 MVA BESS for a 250 MW outage compared to the case of no BESS. The MWh capacity of the BESS does not need to be extremely large to make a significant impact on the frequency response of the system. The frequency response with the addition of BESS has also improved with the addition of BESS, as the response time of a BESS would be faster than that of a governor.

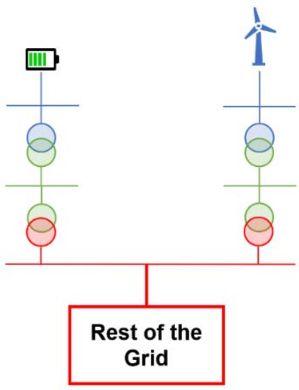

Figure 3
HPP Model

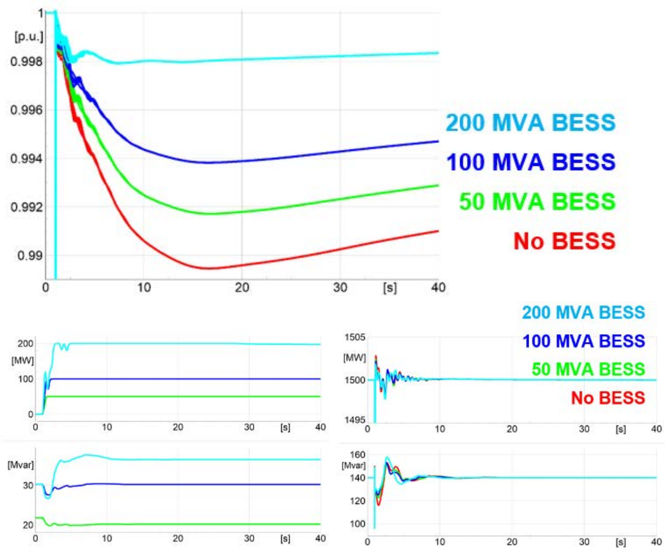

Figure 5
Generator Outage - Generator Frequencies (Top), BESS P and Q Output (bottom left), HPP P and Q Output (bottom right)

Even with a BESS capacity of 2 MWh, with generator frequency response results shown in Figure 6, the frequency nadirs of the BESS simulations are equal to the 10 MWh case, displaying the potential for low-capacity BESS to reduce the frequency impact of outages. However, it is important to highlight the cases where the SOC of the BESS drop to the minimum SOC value, set at 20%. In the case of the 100 MVA and 200 MVA BESS scenarios, this causes the BESS to stop supplying their nominal to the network. This can be alleviated by gradually ramping down the power supplied by the BESS to the network, allowing other dispatchable generators such as gas to gradually take over the slack over an extended period.

When operated correctly, considering the state of charge of the BESS to avoid that second outage, using a BESS could help in preventing the tripping of protection systems and wider outages.

2) *Three-Phase Short Circuit Fault*

A three-phase short circuit at a line close to the hybrid plant was conducted to see if the hybridization of an existing wind farm with a BESS unit improved the frequency response of the network to the fault. The short circuit begins at t=1s and is cleared at t=1.1s. The results from this simulation can be seen in Figure 7. Clearly, the addition of the BESS has indeed improved the response of the network to the fault, with a quicker decay time for the oscillations, and a lower amplitude for the oscillations. A further reduction in oscillations would also be possible with the addition of POD controllers into the BESS units in the system.

B. *EMT Simulations of Hybrid Power Plants*

1) *Introduction*

The previous sections have discussed the behaviour of the hybrid plants and the capability that can be provided by these plants to support system reliability and operation. However, all simulation studies were carried out in positive sequence domain. With many hybrid plants being inverter-based resources such as battery energy storage systems with solar plants, it is important to verify the behaviour of such plants in electromagnetic transient (EMT) domain. Further, it is important to understand the various services that such plants can provide to the network, and the different factors that may impact the provision of such services. With the increase of inverter-based resources (IBRs) in the network, it is also possible that soon, for few hours of the day, many power systems can be 100% fed from inverter-based generation. In this scenario, the performance of hybrid plants, and their potential grid forming capability is to be investigated.

In this scenario, a comparison of simulation results from EMT domain and positive sequence domain are carried out in a 100% inverter scenario. Concepts of grid forming capability and their modelling details are borrowed from references [41], [42].

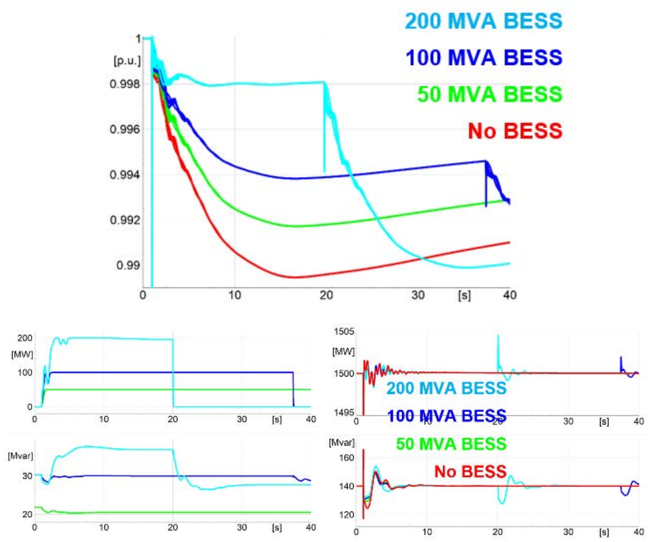

Figure 7
Generator Outage (2 MWh BESS) – Generator Frequencies (Top), BESS P and Q (bottom left), HPP P and Q (bottom right)

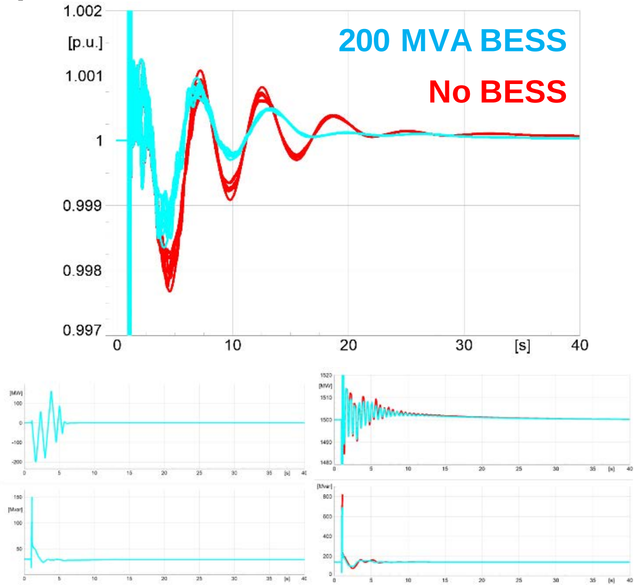

Figure 6
Three-Phase Short Circuit – Generator Frequencies (Top), BESS P and Q Output (bottom left), Wind Plant P and Q Output (bottom right)

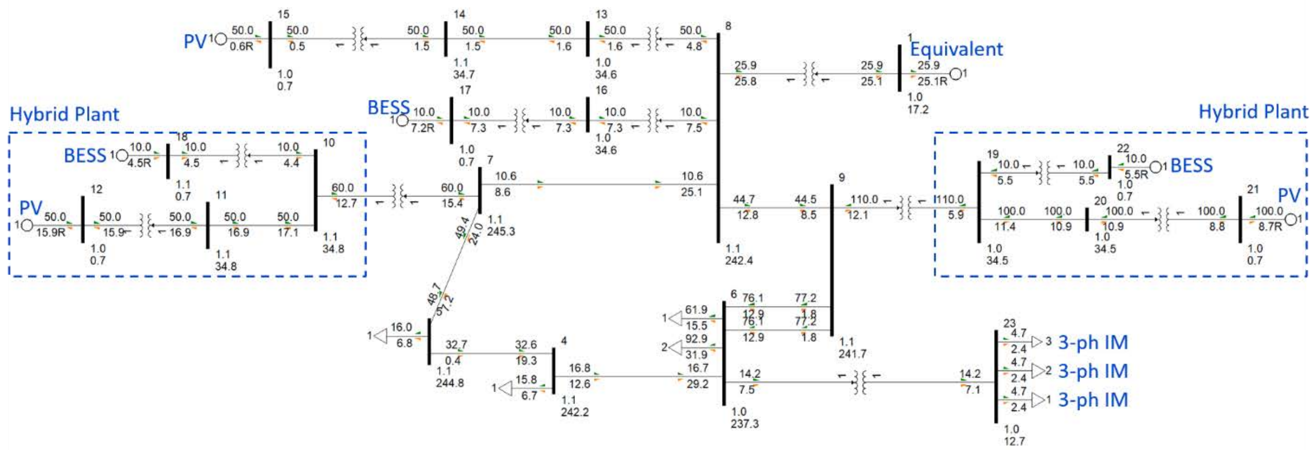

Figure 8
Small system setup used to investigate the behavior of hybrid plants in PSCAD®

2) System setup

To compare the performance of hybrid plants, a test system setup as shown in Figure 8 is used. Here, both HPPs comprise of a PV plant coupled with a BESS on the ac side. The BESS component in each plant is rated at 30 MVA while the PV components are rated at 60 MVA and 110 MVA respectively for the plants connected at bus 10 and bus 9. In addition to these HPPs, the network also contains an additional standalone PV plant rated at 60 MVA connected at bus 8 along with a standalone BESS plant connected at bus 8. These two resources can be considered to co-located resources connected to the same transmission bus. The loads in the system are primarily static loads with constant current active load components and constant impedance reactive load components. In addition, at bus 6, three 3 phase induction motors are connected to represent the dynamics of an industrial load. In EMT domain, all BESS modules in this system are modelled using a base model from PSCAD® and subsequently modified to operate in grid forming mode using the philosophy outlined in [41]. The PV modules are represented in grid following mode using the models discussed in [41], with no frequency support provided by the modules. The first objective of the study is to understand if the system can survive a disconnection from the equivalent system with only the BESS operating in grid forming mode. Further, another objective is to ascertain if similar conclusions can be arrived at from a positive sequence study of the system.

3) Simulation results

The simulation results for a variety of scenarios will be discussed here in this section. In the positive sequence study, the inverters are represented using the new positive sequence REGC_C generic model [43].

a) Trip of System Equivalent resulting in Islanded 100% IBR Network

In the first scenario, it is assumed that once the network reaches a steady state, the system equivalent trips at t=3.0s resulting in the formation of a 100% IBR network. Prior to the trip of the equivalent, the exchange of power is approximately 25 MW/Mvar with the direction of power transfer being from towards the system equivalent. All IBRs in the resultant 100% IBR network have sufficient power and current headroom to accommodate for this change i.e., reduce active and reactive power production. However, here, even though the IBRs must reduce their outputs upon the creation of the island, it can be seen from Figure 9 and Figure 10 that the island is unable to maintain a stable operation. Here, although there are three grid forming resources in the form of three BESS modules in the network, the dynamic response from these devices is not sufficient to maintain reliability. The trace of electrical frequency in the network is shown in Figure 11.

Now, across these figures it can be observed that the responses across EMT domain and positive sequence domain don't exactly show the same type of instability. In EMT domain and oscillatory instability is observed while in positive sequence domain, an exponential instability is observed. However, both responses provide a picture of something being amiss in the network for this operational scenario. From the traces of positive sequence studies, a system planner can make an inference that this operating condition needs more detailed study as the frequency in the island is observed to reach 62.5Hz. Further, the voltage magnitude within the island is shown to reach nearly 1.2 per unit. Both these conditions would violate the operational limits of the network and can cause other elements to trip/disconnect. Using these positive sequence results, a system planner can make a case to carry out further detailed

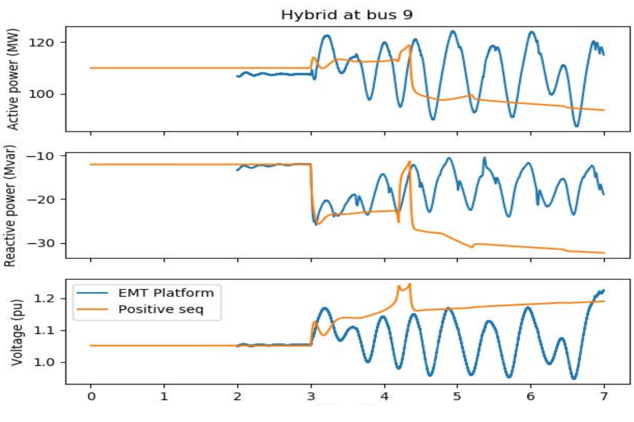

Figure 9
With all PV plants in grid following mode, dynamic response of the hybrid plant at bus 9 upon disconnection of the system equivalent at t=3.0s

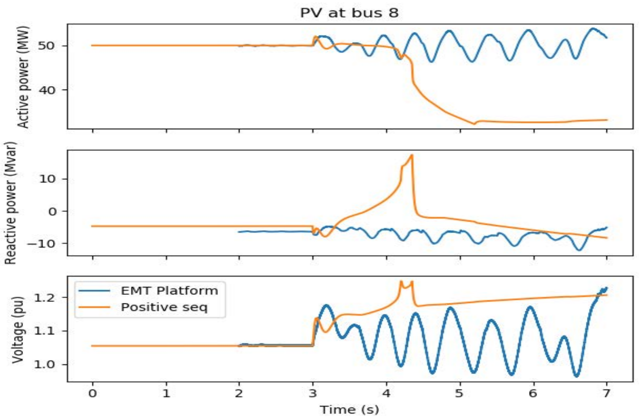

Figure 10
With all PV plants in grid following mode, dynamic response of the PV plant at bus 8 upon disconnection of the system equivalent at t=3.0s

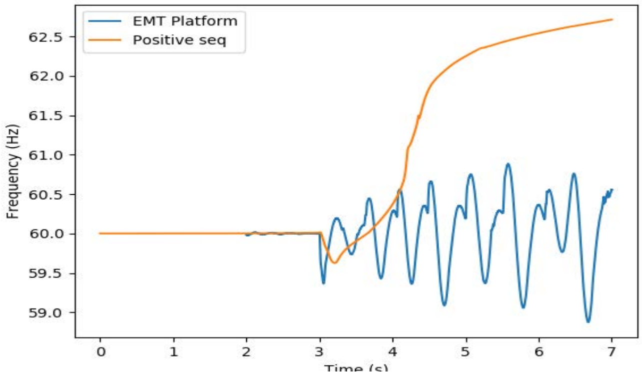

Figure 11
With all PV plants in grid following mode, trace of electrical frequency upon disconnection of the system equivalent at t=3.0s

studies for this scenario. Further improvement in the positive sequence models is to be carried out as future work.

Now, without changing the ratings of any of the devices in the network, the grid following PV modules are enabled to provide frequency support with a ramp rate limit of 10pu/s.

The dynamic response again observed at both the terminals of the hybrid plant at bus 9 and the PV plant at bus 8 is shown in Figure 12 and Figure 13. With the PV plants providing such support, the beneficial impact on the system response can be readily observed both from EMT domain and positive sequence domain. The PV plants actively contribute to reducing their power output in a timely manner which reduces the burden on the BESS modules. As a result, a more stable response is obtained. More details regarding the impact of the value of ramp rate limit is provided in [41].

b) Trip of system equivalent followed by two subsequent three phase to ground faults

The response of the system to three phase faults in the islanded network is shown in Figure 14 and Figure 15. The three phase faults are applied on either side of the induction motor load bus. Here too it can be seen that once the models both in EMT domain and positive sequence domain are parameterized appropriately, the response of the system is equally obtained from both platforms. It should be cautioned that this behaviour is not meant to imply that detailed EMT simulation studies are not required to be carried out. It is instead meant to convey the improvements that are being

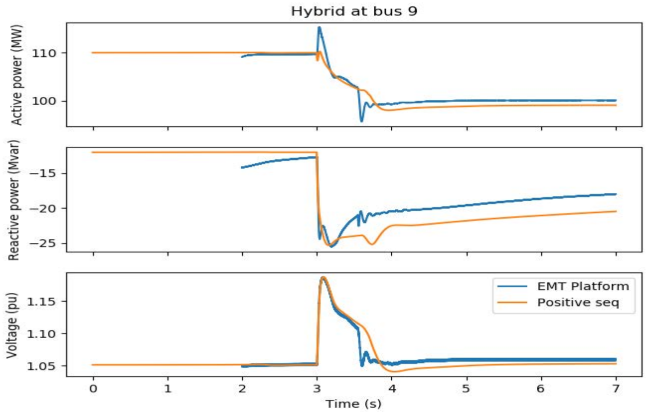

Figure 12
With all PV plants in grid following mode but providing frequency support with a ramp rate limit of 10pu/s, dynamic response of the hybrid plant at bus 9 upon disconnection of the system equivalent at t=3.0s

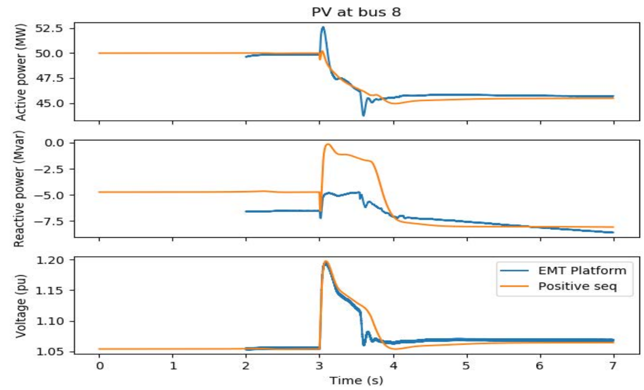

Figure 13
With all PV plants in grid following mode but providing frequency support with a ramp rate limit of 10pu/s, dynamic response of the PV plant at bus 8 upon disconnection of the system equivalent at t=3.0s.

made in positive sequence simulation models that can allow a transmission planner to obtain more visibility into the behaviour of future power networks.

An aspect related to the importance of the ramp rate limit of the output from PV plants is highlighted here for these events. Comparing two ramp rate limits of 1pu/s and 10pu/s, Figure 16 shows the response of the hybrid plant at bus 7, the electrical frequency and the speed of the three induction motors. In this plot, only the EMT simulation results are provided. With a lower ramp rate limit from the PV plants, the induction motors are susceptible to stalling. Upon the clearance of the fault, since voltages are restored in the network, the loading of the motors also increases. However, with the PV plants not increasing their power output in a timely manner, a voltage collapse condition could manifest which results in induction motors not being able to generate sufficient electrical torque. With the higher ramp rate limits, the fault ride through behaviour of the network improves allowing for the motors to re-accelerate in a suitable manner

These results showcase the intricacies involved in determining performance characteristics to being about stable operation of a network with hybrid plants. Both from an EMT modelling perspective and a positive sequence modelling perspective, the availability of adequately parameterized models is critical in being able to efficiently run numerous scenarios and studies that can lead to a good definition of

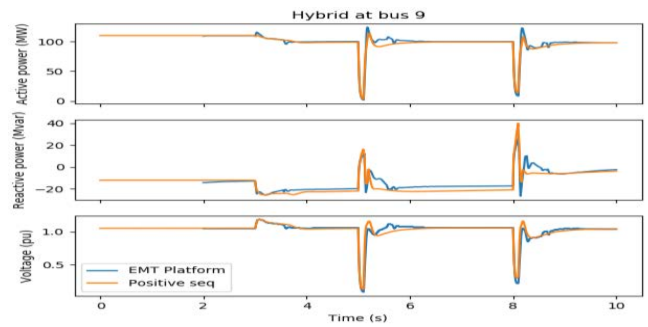

Figure 15
With all PV plants in grid following mode but providing frequency support with a ramp rate limit of 10pu/s, dynamic response of the hybrid plant at bus 9 upon disconnection of the system equivalent at t=3.0s and two subsequent three phase to ground solid faults

performance requirements. The results shown here are encouraging as they provide an insight into the improvement of simulation models and study scenarios to be considered. Future work will continue the development of these models and scenarios.

V. CONCLUSION

The main results of the studies described in this chapter can be summarized to state that inclusion of only BESS in grid forming mode may not be sufficient for a system unless either many BESS or a large rating of BESS in grid forming mode is considered. This result will be important for planning studies as it may mean that requests in generation interconnection queues may have to be evaluated with consideration of more study scenarios. Further, the response of the system is not the burden of only the energy storage elements. It is important to consider the response from other resources too and pay close attention to the ramp rate limits of devices and the characterization of load dynamics. Considering induction motor load versus static load behaviour can provide different response characteristics which can change the final study results. Finally, although the comparison of results across software platforms is encouraging, continuous improvement of models across software platforms is to be carried out.

VI. FUTURE WORK

We aim to investigate HPPs with a single plant controller, as opposed to the co-located plants that were investigated in

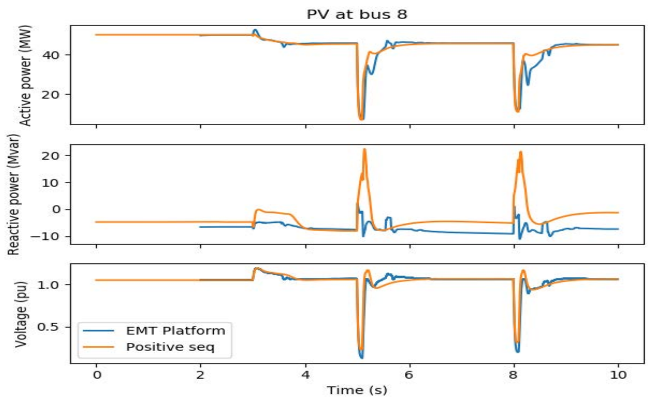

Figure 14
With all PV plants in grid following mode but providing frequency support with a ramp rate limit of 10pu/s, dynamic response of the PV plant at bus 8 upon disconnection of the system equivalent at t=3.0s and two subsequent three phase to ground solid faults

the RMS domain simulations, investigate the coordination between the different plants within the HPP and observe any potential controller interactions that could affect the stability of HPPs. Observing any presence or reduction in interactions due to the single plant controller will be an interesting study case.

There will also be a focus next year on the link between HPPs and resource adequacy and optimize the relationship for storage elements to provide for peak loads and frequency response during an event.

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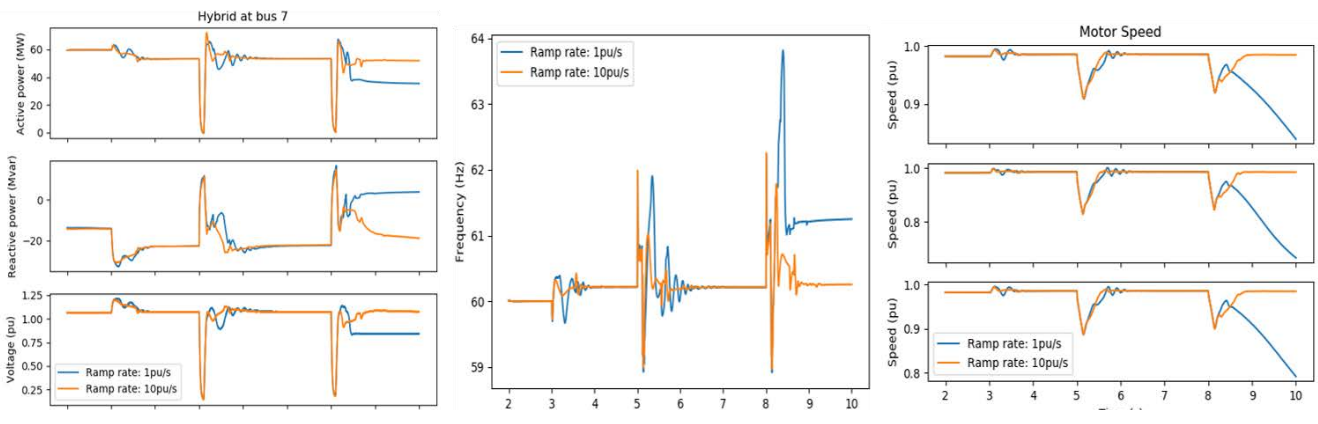

Figure 16
With all PV plants in grid following mode but providing frequency support with a ramp rate limit of 1pu/s or 10pu/s, dynamic response of the hybrid plant at bus 7 (left), electrical frequency (center) and induction motor speed (right) upon disconnection of the system equivalent at $t=3.0s$ and two subsequent three phase to ground solid faults

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