RECENT ADVANCEMENTS ON POWER SYSTEM RESTORATION

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Abstract—**Traditional and current restoration strategies use top-down approach that rely on the use of centralised conventional generation such as hydropower plants and gas power plants to start up the network after a wide area blackout. Analysis of restoration steps is also based on AC networks with no involvement of DC schemes. The distribution network has also been assumed to be passive having to wait for the transmission scheme to be stable. Today and future restoration strategies should align with the changing network paradigm. Prediction of high penetration of renewable resources coupled with increasing DC schemes demands change in restoration strategies. A review of role of Wind Power Plants, HVDC, BESS, SST and WAMS in the restoration process is presented in this paper.**

Index Terms—**BESS, HVDC, Power system restoration, SST, Wind Power Plant, WAMS.**

I. INTRODUCTION

Blackouts are categorised as low probability high impact events and the fact that they are limited means that there is limited experience in dealing with network restoration after widespread blackout. Power system restoration is the process of network energisation after a complete or partial blackout. There are 3 main phases related to the restoration of power networks: damage assessment, repair and reenergisation. Under the reenergisation phase, there are three major stages of restoration: unit start-up, network reconfiguration and load restoration [1]. The first stage, unit start-up, is commonly referred to as the black-start stage where units that do not require external support are started. Traditional black-start units include large hydro power plants and combustion turbines (gas power plants). Thermal power plants can be used as black start units depending on how long they have been off after the blackout and if they have been equipped for load rejection capabilities. Nuclear power plants, after a blackout, require a complex process first to shut them down, then prepare them for restoration participation. The second stage of restoration is network reconfiguration that involves energisation of major transmission lines and cranking up of non blackstart units. Load restored in either the 1st or 2nd stage is required for stabilisation purposes. Temporary network islands also form as a result provided the island formation requirements are met as described in reference [2]. The last stage of system restoration is the restoration of loads, including energisation of MV and LV substations, that have not been restored in the 1st and 2nd stage. The main consideration during power system restoration is minimum restoration duration considering the safety margins of the network.

Different review papers have been published to keep an update on the restoration processes. Reference [1] keeps a record of all the major publications of the 20th century while Reference [3] summarises last 10 years of power system restoration research. Dynamic restoration issues related to voltage and frequency control have been explained in references [4] and [5] with reference [4] suggesting appropriate control strategies in solving the mentioned challenges. Key issues during the planning process of restoration has been summarised in reference [6] with reference [7] providing a review of the effect of a liberalised market and decentralized control in power system restoration.

This paper reviews the restoration process in the context of participation of emerging technologies such as HVDC, wind generation, WAMS, Solid State Transformer and storage. Section I gives an introduction of the overall restoration process in the traditional paradigm. Section II and III summarises research on the restoration role of windfarms and HVDC transmission respectively after which Section IV provides a summary of work done on the use of BESS and Solid-State Transformer in the restoration process from a microgrid point of view. Section V summarises work done on use of synchrophasor technology during the restoration process. Conclusion and proposed future works in restoration are provided in section VI.

II. WIND POWER PLANTS

Participation of windfarms in restoration has been limited due to its intermittent nature and lack of dispatchability [9]. Different aspects of windfarms during the restoration process have been investigated and discussed in [8,10,11,12]. The third stage of restoration in the top-down approach has been proposed as the best stage for windfarms to participate as the network is stable. Reference [10] takes advantage of the improved controllability of active and reactive power, accurate short-term wind generation forecasting and the use of dynamic programming to pick up load taking into consideration wind uncertainty and dynamic issues during restoration. The optimum amount of wind power to be used at each restoration stage is proposed in references [8] and [11] using chance constrained programming and firefly optimisation

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respectively. It is foreseen in [13] that self-control of windfarms can be made possible by the use of VSC-HVDC interconnection and this creates the possibility of its use during black start [13]. This is seen in reference [12] as the participation of windfarms is not only limited to load pickup but also voltage and frequency control. The wind turbines within the windfarm are not energised at once but in clustered groups. Hybrid schemes are proposed in [14,15] as shown in figure 1. with [14] containing a 150 MW windfarm, combustion turbine and STATCOM with the combustion turbine providing external power required for the windfarm to operate and STATCOM to provide additional reactive power control. Its participation is still limited to active power/frequency control as load is being picked up. Reference [15] considers use of virtual inertia in PMSG based wind turbines to enable the windfarm to participate in frequency control. The diesel generator is used to provide the voltage and frequency setpoints while the STATCOM provides the voltage support during restoration.

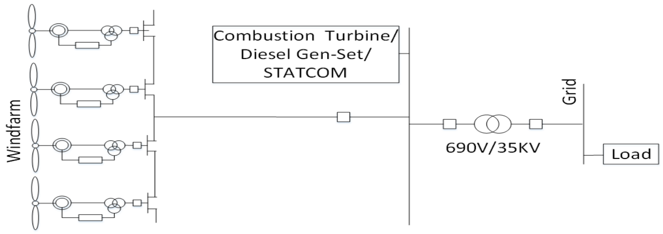

Figure 1: Windfarm Hybrid Scheme

Wind storage systems shown in figure 2 with the storage element either connected at the PCC or dc link have been proposed in references [16-19] as a feasible way of using wind turbines in the first stage of restoration. The storage system, located at the dc link, is to provide the initial excitation and handle transients associated with changes associated with dc link capacitor. ESS at the PCC is better used for long term power management. It is thus required to have a storage element of high power density such as supercapacitors or flywheel storage system at the dc link while having high energy density ESS at the PCC. Reference [17,19] provides the control model while the importance of charging and discharging characteristics during black start has been studied in reference [18].

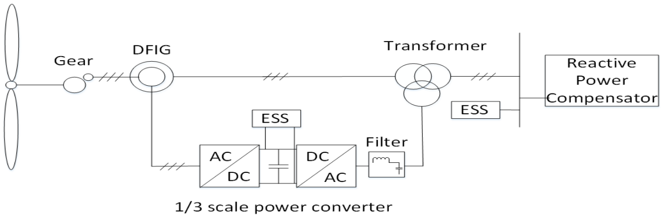

Figure 2: Wind Turbine Storage System

III. HVDC

High Voltage DC transmission schemes are being used for long distance bulk power transmission, underground submarine cable transmission and interconnection of asynchronous networks. There are currently 2 types of HVDC technologies: LCC HVDC and VSC HVDC. LCC HVDC is thyristor based and depends on natural commutation for switching on and off. It is commonly used due to its established technology and low switching losses compared to VSC-HVDC. Requirement for stable voltage (for commutation) at the receiving network has limited the participation of LCC HVDC interconnection in the restoration process. LCC-HVDC is also unable to operate with in-house load only due to production of discontinuous current under minimum load. Recent research [20-22] has tried to improve its participation with [20] presenting the effect of different start-up modes of LCC HVDC on active and reactive power. This is in order to have less active power for minimum load and enhanced reactive power control required during restoration process. Use of SCR (to satisfy voltage requirements) and inertia (to satisfy frequency requirements) during restoration are proposed in [21] also to determine the optimum time to start up the HVDC. Out of the different control and start-up modes, the CV (at the rectifier) - CC (at the inverter) control mode and 70% reduced voltage start-up mode were chosen to minimise the active power impulses [20,21]. To eliminate the effect of discontinuous current under minimum load, reference [22] proposes the use of bipolar pseudo-deicer mode in which one pole of the sending end runs in rectifier mode while the other pole runs in inverter mode. The same configuration runs in the receiving end and by proper control net power at the receiving end can be controlled.

LCC HVDC hybrid schemes as shown in figure 3 are proposed in [23-25, 36]. Reference [23,24] proposes the use of Synchronous Compensator to provide adequate commutation voltage to start up the LCC-HVDC in a passive network with the only requirement being connection of load within the first 5 minutes of starting. STATCOM instead of the combination of synchronous compensator and diesel generator is proposed in [36]. Control of LCC HVDC to blackstart a passive network without additional equipment such as STATCOM or Synchronous compensator is proposed and tested in [25]. Voltage, frequency and extinction angle control were achieved, and this ensured continuous commutation, voltage amplitude regulation and acceptable steady state extinction angle.

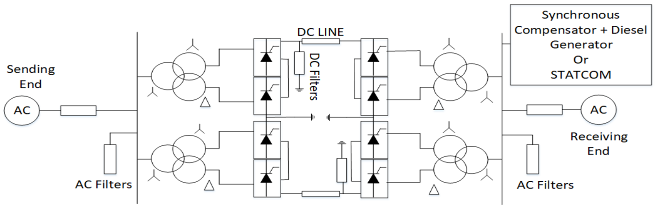

Figure 3: LCC HVDC Hybrid Scheme

Recent developments on high voltage rated IGBTs, ability to self-commutate and four quadrant operations have made VSC-HVDC superior to LCC HVDC. Their use is still limited due to less power transmission compared to LCC HVDC largest VSC based link being Estlink which is a HVDC connection between Estonia and Finland with a rated capacity of 350 MW. In terms of restoration; improved low voltage ride through, self-commutation capabilities and independent control of active and reactive power [26] have led to consideration of VSC-HVDC in black-starting of a passive network. Different control modes are proposed in [27] with their stability using root locus technique investigated at different stages of the restoration. This configuration assumes the rectifier at the sending end is always working in constant current mode. Reference [28] proposes a PI control strategy to soft start-up a VSC-HVDC connection. This is to aid in elimination of the effect of switching surges resulting from energisation of long transmission lines at no load. Reference [29] extends the principle of soft start to eliminate the effects of transformers and motor loads during restoration. It also evaluates the control mode change over from active voltage control to active power-voltage control after energisation of a non-black start unit. Simulation/experimental studies in [30, 31] have shown stable operation of VSC-HVDC during load changes and fault occurrence during the restoration process. Use of HVDC with a suitable control strategy has also been proposed in [32] to eliminate the issue of reactor hunting as a result of voltage fluctuations during initial stages of restoration. Multiple cases and field studies on the use of HVDC for black start are given in [22, 33-35].

Reference [37] considers the operation of combination of LCC HVDC at the rectifier side operating at DC voltage control mode while the VSC HVDC at the inverter side operates in AC voltage control mode. It is assumed that the inverter side has no synchronous generation and power flow will be in one direction only. Simulation under load changes, faults and load shedding show increased performance.

IV. BATTERY ENERGY STORAGE

Storage is deemed to be the most important component in integration of renewable energies [38]. Participation of storage in the last stage of restoration (load restoration) is proposed in reference [39 – 41] with reference [39] assuming a microgrid environment in which the DFIG has no droop control thus only conventional generation and storage participate in load restoration. An operating strategy for the battery as both load and generator during restoration is proposed in [40]. It is highly dependent on charging and discharging capabilities. Reference [41] proposes an optimal battery size for frequency regulation assistance in the restoration period. Reference [23,42-46] considered use of storage as black start sources to provide cranking power to NBS units with [42] providing an optimized BESS control at both the initial and last stages of restoration. Use of electric vehicles through battery swapping to provide cranking power to NBS units has been proposed in reference [43]. Reference [23] provides a case study that combined the use of BESS and STATCOM to provide cranking power of about 27 MW for about 15 minutes. This was considered enough for initial restoration. Benefit of ramping up voltage during battery energisation and battery dynamics during restoration are presented in [44] by use of RTDS. Reference [45] shows the Improvement in restoration time using VRBs (Vanadium Redox Battery) as a black start source with [46] considering combinational use of both lithium ion and VRBs batteries in the restoration process of microgrids. The lithium ion batteries are considered as the black start source responsible for voltage and frequency control while the VRB based battery system operates in PQ control method after the lithium ion battery system has ensured frequency and voltage stability. Lastly, the PV is incorporated into the black start process depending on the resource availability. Detailed models for solid oxide fuel cells and single shaft microturbines coupled with storage facilities for black start studies are provided in reference [47]. Their respective inverters are operated in voltage control mode with frequency droop characteristics to emulate the behavior of a synchronous generator. Power from wind and solar energy will be used in the subsequent restoration process.

V. SOLID STATE TRANSFORMER

Solid state transformer has been put as one of the emerging technologies in power electronics. It is deemed to be the next distribution transformer in smart grids [53]. Voltage transformation through the SST is achieved firstly by changing the frequency from 50 Hz to around 10 KHz after which the high frequency voltage signal is transformed to the value required then lastly, the signal is changed back to the system's nominal frequency [53]. The high frequency voltage transformation leads to reduction in size of the transformer thus reduction in transformer energising currents. Also, the use of power electronics means more control is available to the utility. Figure 4 shows a basic SST scheme.

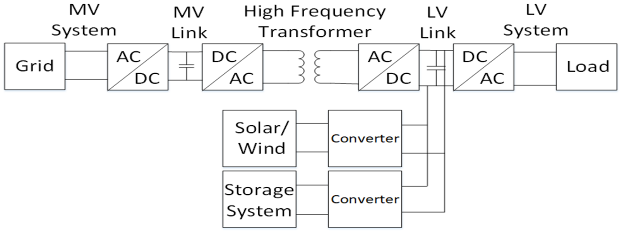

Figure 4: Solid State Transformer Scheme

Reference [54] investigates the performance of a 20KVA SST during black start. Complete decoupling between the load and generation is achieved thus allowing use of simple droop control schemes. Detailed modelling of the SST, local load inverter, dual active bridge, battery bidirectional buck/boost, PV panel boost converter is provided to improve accuracy of simulation. Reference [55] proposes a master-slave approach (instead of the parallel mode-droop) in use of the SSTs in black start restoration. It is assumed that communication will be available. DQ equations have been derived for both the rectifier, grid tie inverter mode and black-start mode. The master SST is chosen as the one with the largest DER and can operate in standalone/inverter mode, the other generating SSTs operates in grid tie inverter mode and the load SST operates in the rectifier mode. According to figure 4, the LV link is first energised by the storage system after which the solar/wind is used to pick important load. The HFT is then energised and MV link energised to enable more generation connected at this link to pick up load.

VI. WAMS

Synchrophasors which are GPS based and time stamped provide accurate real-time measurements of the network [51]. In power system restoration, the power network is constantly changing thus information of the network is essential to avoid another collapse during restoration. Inability of the network components not to function during a blackout limits the observability function during restoration process. References [52 -61] have explored the use of PMU data and WAMS to improve the restoration process in the 2nd and 3rd stages. A method to pre-determine the island/subsystem formation and weak areas after a blackout has been proposed in reference [52] after which reference [53] proposes the best locations for PMU placement to avoid collapse of the formed islands. Reference [54] considered the use of integer linear programming to solve the optimal PMU placement problem with [55] introducing an observability constraint to be used in determination of the islands to be formed after blackout. At least one PMU is required for each island. Use of WAMS in the last stage or restoration to determine the suitable generation or load steps is considered in reference [56 – 58] with reference [58] also considering power output from DFIG based wind generation. Reference [59] and [60] use PMU data to determine the standing phase angles to ensure safe resynchronisation of two formed sub-systems/islands. A case study of the Gustav 2008 storm has been presented in reference [61] to show the benefits of phasor measurement units in maintaining the stability of the Baton Rouge-New Orleans area that operated as an island.

VII. CONCLUSION AND FUTURE DIRECTIONS

A summary of the recent developments in power system restoration has been given in this paper. Since wide area blackouts are rare, experience with the restoration strategies is limited in practice. The changing network paradigm with increased penetration of large wind power plants and proposed solar farms necessitates the change in restoration to accommodate the changes. Each additional network equipment should be analyzed not only during normal and fault conditions but during also restorative mode.

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