Control of Active Distribution Networks

Report By: Soham Deepak Koyande (21D170040)
Guide: Professor Suryanarayana Doolla

1. Abstract

The growing demand of electricity in human society and the need to do it in a clean manner have made the installation of distributed generators (DGs) increase day-by-day. The conventional distribution network consists of only generators located centrally and loads at different buses. However, with the increase in roof-top solar PV and with the advent of the new Vehicle-2-Grid technology, power is also injected from the customer side. This transforms the distribution network from a passive network to an active distribution network (ADN). The small X/R ratios of low voltage (LV) networks make the system prone to voltage and frequency deviations, especially during peak load times and peak solar generation times [1]. It is necessary to provide good power quality despite this change in the nature of the LV network.
This can be done either by using optimisation techniques to cater to the fast-changing load and generation like the virtual synchronous generator (VSG). This seminar report highlights the existing control techniques in ADNs found in literature, with a focus on new control architectures in transformers and VSGs. A comparison of a few VSG methods is also done to show that each has their own features and use cases with the synchronverter being the best in a weak system. Examples of small-scale demonstrations in a microgrid are also recognised, along with a few research directions in control of ADNs.

Keywords: Active Distribution Network, Virtual Synchronous Generator, Unbalanced Grid,

Nomenclature

Abbreviations

ADN	Active Distribution Network
BESS	Battery Energy Storage System
DER	Distributed Energy Resource
DG	Distributed Generator
FRT	Fault Ride Through
GFLI	Grid Following Inverter
GFMI	Grid Forming Inverter
IBR	Inverter-Based Resource
KHI	Kawasaki Heavy Industries
LV	Low Voltage
OLTC	On-load Tap Changer Transformer
PCC	Point of Common Coupling
PI	Proportional-Integral controller
PLL	Phase Locked Loop
PSC	Power Synchronisation Control
RMS	Root Mean Square
SCR	Short Circuit Ratio
SM	Synchronous Machine
SPC	Synchronous Power Controller
THD	Total Harmonic Distortion
VESS	Virtual Energy Storage System
VISMA	Virtual Synchronous Machine
VSG	Virtual Synchronous Generator
VVR	Voltage/VAR

Symbols

C	Capacitance, C
D	Damping constant
E	Field Voltage, V
I	Current, A
J	Inertia constant
L	Inductance, H
m	modulation
P	Active Power, W
Q	Reactive Power, VA
R	Resistance, Ω
s	Laplace variable
V	Voltage, V
X	Reactance, Ω
δ/θ	Rotor Angle
ω	Frequency, rad/s

Subscripts and superscripts

abc	abc frame
dq	dq frame
f	filter/ frame
g	grid side
n	nominal/rated
ref	reference value
set	set point

2. Introduction

The conventional Voltage/VAR (VVR) control devices like on-load tap changer transformers (OLTC), step voltage regulators, capacitor banks, are classified as slow regulating devices because of their slow time scale compared to the inverter-based resources (IBRs) [8]. Also, these are designed for only a few changes in their setting over their lifetime before they start deteriorating. In a network with frequent injection of power, and large load demands, the voltage keeps fluctuating very frequently and using conventional VVR devices is not feasible unless optimisation is done [1]. The current grid protection schemes are not designed for the smaller overcurrent design of IBRs, so a possible fault in the network is seen as a disturbance and hence protection systems do not function in their intended manner.

3. Optimisation-Based Solution

The usual way to tackle this problem is to define an objective function (like min. power loss, satisfaction of voltage limits, max. active power output, etc.), define constraints and use an optimisation technique (eg. droop based, droop free decentralised solution etc.) to solve the problem. Many of these techniques are listed in [1] and [2]. The authors also highlight the need to define the communication method used in solving the problem, with choices between a centralised, decentralised or a distributed control.

An example of such an optimisation problem is the use of virtual energy storage system (VESS) coordination proposed in [3]. This paper has provided hierarchical dispatch strategy to control the residential air conditioner load, with objective function to maximise the controllable VESS capacity available with an aggregator, with constraints on the comfort level of the user. It aims to increase the active power consumption during peak PV generation and reduce during peak load. The authors claim to reduce the net cost of installing battery storage system (BESS) when such a method is used.

In [4] a comparison of transformers (line frequency transformer, solid state transformer and hybrid transformer) is presented. They have given a decentralised voltage control method using BESS. In [5], an alternative to the optimal power flow solution is given with significantly less communication requirements. [6] provides a droop-based control method, to minimise the reactive power deviations in a combined local and centralised voltage control. This also reduced the number of tap changes required.

4. Control Architectures

Before introducing the available control methods/ block diagrams in literature it is important to understand the types of IBRs and their behaviour. [7]
Depending on the interaction with the grid, controller implementation and response to grid changes, IBRs can be classified as grid following inverters (GFLIs) and grid forming inverters (GFMIs).
In the installed IBRs, the power extracted is based on the maximum power point tracking mechanism used to inject the most amount of power available. This is done due to the intermittency of renewables and the low penetration of such devices in the grid. They are made to follow the grid voltage using phase locked loop, which makes them similar to a current source. These IBRs are called grid following inverters (GFLIs). Their primary objective is to inject the max. power, with reactive power support only if it is mandated. In contrast, the GFMIs do not follow the grid voltage instead create their own reference voltage (a feature which was the reason GFMIs were first used in the islanded operation of microgrids). Their primary objective is to regulate the voltage and frequency of the grid. So, the active and reactive power reference values are changed continuously. The control methods which will be discussed further can be applied to both GFLIs and GFMIs to provide regulation, but the speed, stability margin, cost and extent of doing so is different. Table 1 compares them both on these criteria [7].

Table 1: Comparing GFLI and GFMI [7]

Parameter	GFLI	GFMI
Inertial Response	Not intrinsic	Intrinsic
Cost	Low	High (due to oversizing for fault current emulation feature)
Speed	Slow (due to voltage and current measurements)	Fast (due to intrinsic voltage creation)
Stability Margin	Smaller (due to reliance on measurements prone to noise)	Larger (due to self synchronisation ability)

The voltage and frequency of the point of common coupling (PCC) can be controlled by the active (P) and reactive power (Q) injection/ input. The extent of the effect each has on voltage and frequency depends on the distribution network X/R ratio. For high X/R ratio, P controls the frequency, and reactive power controls the voltage. In case of low X/R ratio, P controls the voltage and Q the frequency. In case the ratio is close to one, then there is a coupling between all the parameters. To bring the control methods to a common form of control it is possible to shape the connecting line seen by the IBR to be predominantly inductive using a virtual impedance loop [7]. Figure 1 shows all the control strategies developed till now in literature [8].

Droop based control is the most developed and used control method. The basic working is to assume a linear relationship between the control parameters. A low pass filter is placed along with the droop coefficient to filter out the higher harmonics. These are used when the X/R ratio is high. It is very easy to implement in a large power network since no communication is required. The droop coefficient is decided based on the rating of the IBR. However, they do not possess the inertial characteristics which are desirable in a high IBR penetration ADN [8].

VSG based control methods try to emulate the behaviour of a synchronous machine. In a synchronous machine (SM) P is controlled by the mechanical swing equations and the field magnitude determines the reactive power Q. Voltage and frequency are controlled by the exciter and speed governor respectively. The VSG control methods try to emulate the inertial and damping response of a SM, by using its model equations with varying amounts of complexity [8].

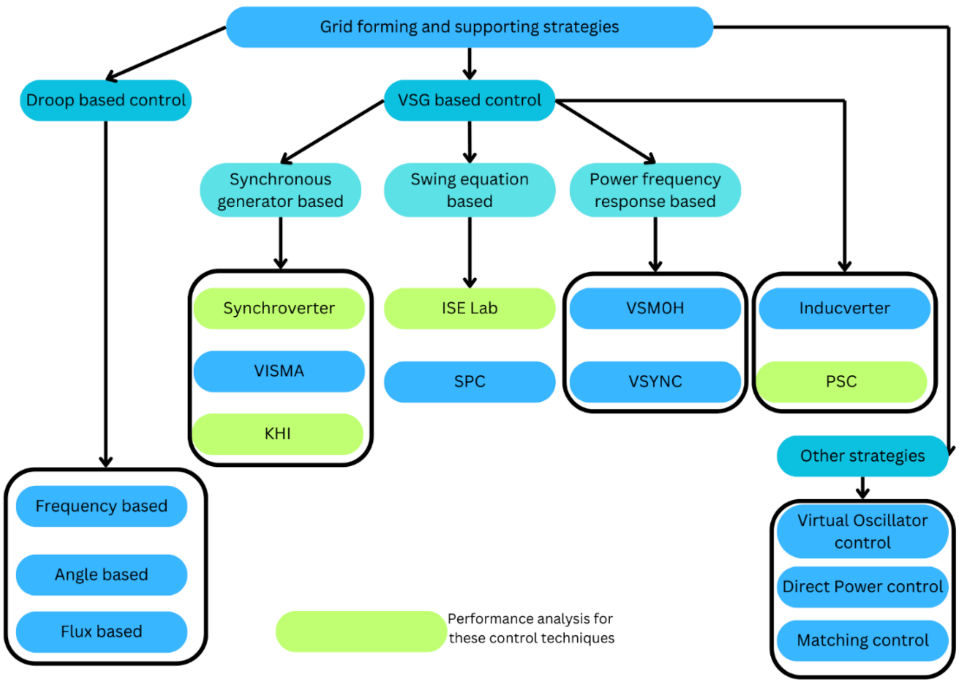

Figure 1: Classification of GFMIs and GFLIs based on control method [8]

VISMA and Synchronverter: These use the most detailed representation of a SM, considering the damper and stator windings, field and rotor mechanical equations. This makes the control method complicated and introduces small scale oscillations in the small signal stability test response. However, they are best for providing the inertial and damping response. It is better than a conventional SM, because the inertia and damping constant can be changed.

KHI: This is a droop-based scheme but placed in the SM based classification because it uses a virtual impedance loop to emulate the stator windings of SM. It can provide the steady state response of SM but the transient response is very slow because it does not employ a dedicated voltage control.

ISE Lab and SPC: These employ only the swing equations of a SM. They are the simplest representation of VSG, which can provide reactive power control which is not the case with VSM0H and VSYNC.

Inducverter: Instead of a SM, an induction machine model can be used to control the IBR. However, due to it being able to feed a constant P and Q, sometimes there can be system stability overshoots.

PSC: It is used to address issues in weak grid conditions (low short circuit index). It is an integral controller so the steady state error will be zero.

Figure 2 gives the active and reactive power control loops of 4 prominent control methods. Figure 3 gives the overall network and the flow of control and equations 1 through 4 give the transfer functions of P and Q with changes to phase angle and voltage magnitude in a network to perform small signal stability analysis [8].

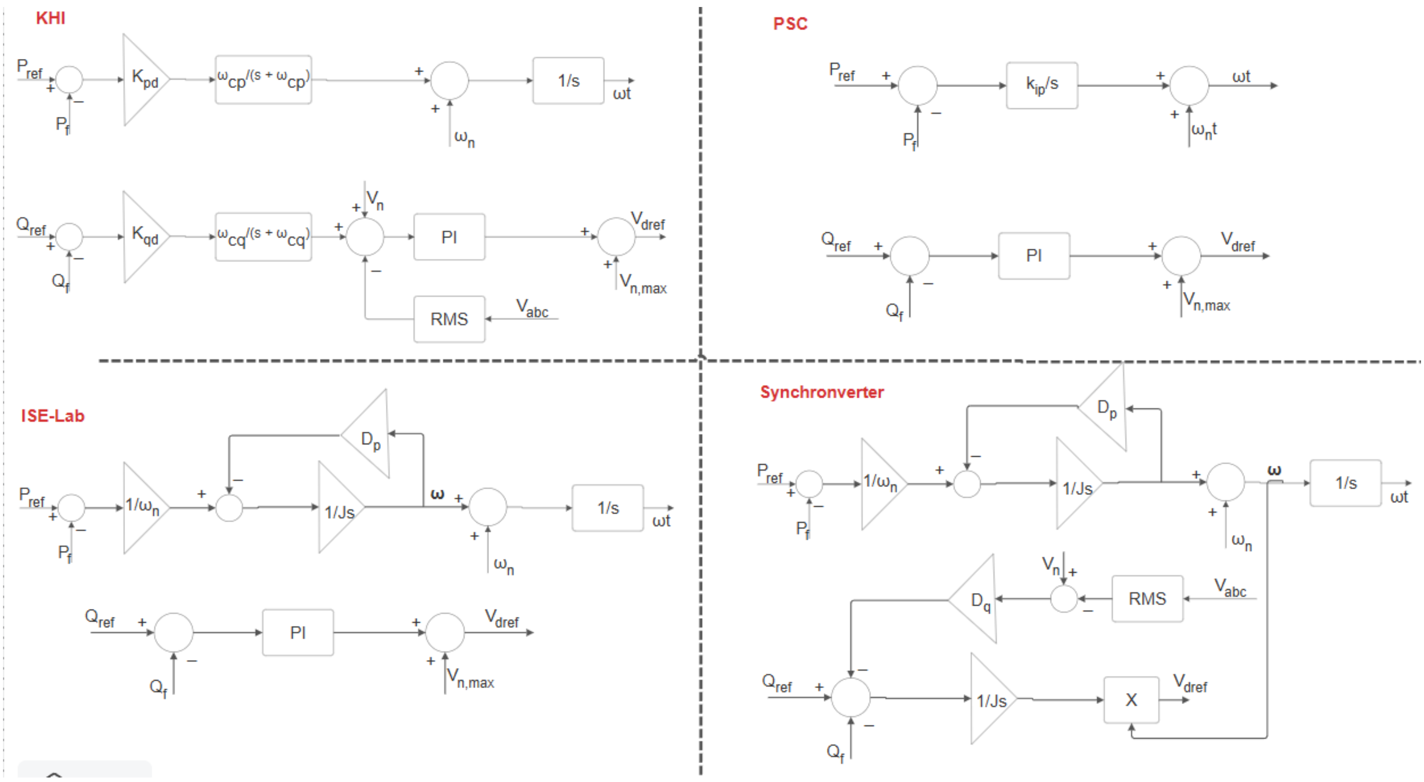

Figure 2: Active and Reactive Power control block diagrams [8]

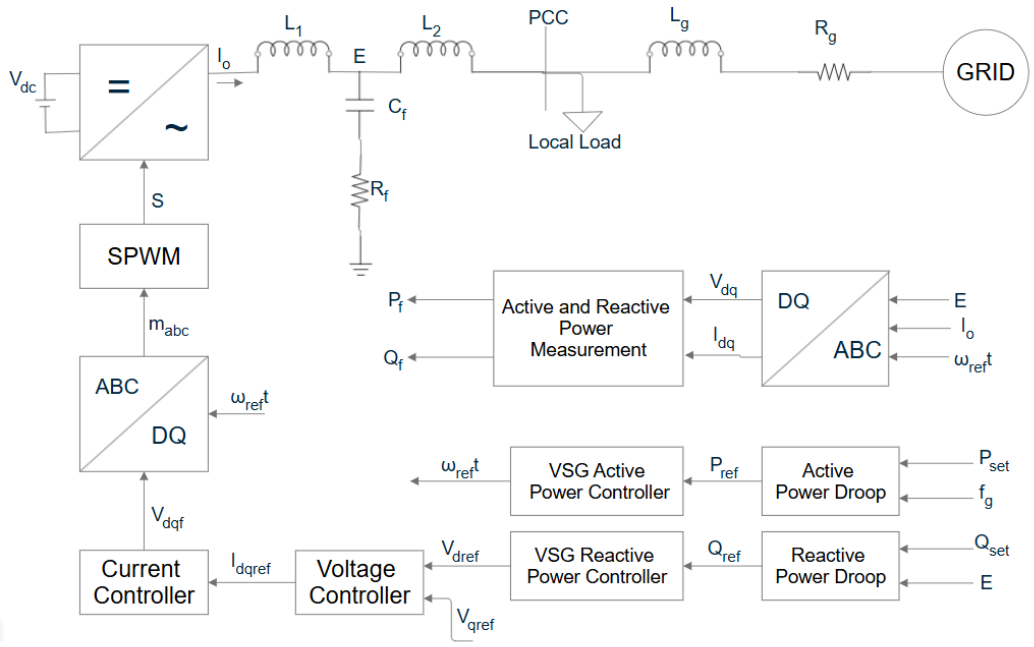

Figure 3: VSG based control architecture [8]

$$\frac{\Delta P_e}{\Delta \delta} = H_{\{11\}} = \frac{\{3(E_0 V_g R \sin \delta_0 + E_0 V_g X \cos \delta_0)\}}{\{2(R^2 + X^2)\}} \tag{1}$$

$$\frac{\Delta Q_e}{\Delta \delta} = H_{\{21\}} = \frac{\{3(E_0 V_g X \sin \delta_0 - E_0 V_g R \cos \delta_0)\}}{\{2(R^2 + X^2)\}} \tag{2}$$

$$\frac{\Delta P_e}{\Delta E} = H_{\{12\}} = \frac{\{3(2E_0 R - V_g R \cos \delta_0 + V_g X \sin \delta_0)\}}{\{2(R^2 + X^2)\}} \tag{3}$$

$$\frac{\Delta Q_e}{\Delta E} = H_{\{22\}} = \frac{\{3(2E_0 X - V_g X \cos \delta_0 + V_g R \sin \delta_0)\}}{\{2(R^2 + X^2)\}} \tag{4}$$

[8] performs the small signal stability analysis and transient analysis for these 4 control methods. The authors study the ability of the controllers to regulate (damping and inertial ability, steady state error) a sudden load addition (both active and reactive). It is seen that for high X/R ratios all can provide good damped performance, but it deteriorates for ISC-Lab and PSC response as X/R is reduced. This is analysed by the pole zero plot of the closed loop transfer function. KHI and Synchronverter responses are always damped without any oscillations.

KHI is not able to provide a good P and Q control due to its current regulation done by a virtual impedance loop, and not a dedicated voltage control. So, when a load is connected, the PCC voltage drops and the control architecture tries to compensate for this drop. One advantage of KHI is its ability to have very less current harmonic content when a non-linear load is connected, this is again due to the controllable virtual impedance acting like a filter to the harmonics.

ISE-Lab behaves particularly poorly under weak network conditions and PSC loses stability for low X/R ratio. This is due to the coupling between P and Q control, which could be tackled by using a virtual impedance loop [7].

All controllers are able to ride through a symmetrical fault. The paper does not study unsymmetrical faults.

Overall, the performance of the synchronverter was found to be better suitable in case of weak grid conditions (low short circuit index) which would be the situation under high IBR penetration.

Table 2 (a to c) [8] shows the results of the performance comparison.

Table 2a: Active and Reactive power response

VSG Based GFMI	Damping and inertial response (Active power)	Damping and inertial response (Active power)	Zero steady state error	Decoupled performance (X/R >5)
ISE-Lab	✓	✗	✓	✓
Synchronverter	✓	✓	✓	✓
KHI	✗	✗	✓	✗
PSC	✗	✗	✓	✓

Table 2b: Load response

VSG Based GFMI	Static and Dynamic Loads		Non-linear loads	
	F_{nadir} < 48 Hz	V_{min} < 235 V	V_{THD} < 5%	I_{THD} < 15%
ISE-Lab	✓	✓	✓	✗
Synchronverter	✓	✓	✓	✗
KHI	✓	✗	✓	✓
PSC	✓	✓	✓	✗

Table 2c: Response under different load conditions

VSG Based GFMI	Stability under different conditions		FRT Performance under symmetrical loads
	When X/R = 1	When SCR = 1	
ISE-Lab	✗	✗	✓
Synchronverter	✓	✓	✓
KHI	✓	✓	✓
PSC	✗	✓	✓

5. Unsymmetrical faults

In ADNs the injection of power from any phase of the 3-phase system can lead to imbalance in the grid. This leads to the creation of negative and zero sequence components. Unsymmetrical faults have not been addressed in the papers discussed till now. [9] has employed a VSG based power control and has integrated a quasi-proportional resonant voltage and current control loop.

4.1 *DC link Voltage control*

A simple VSG active power and reactive power control loop are sufficient for a balanced system. But imbalances in the grid side are seen as a 2nd harmonic imbalance in source-load side and vice versa. So, it is important to suppress the negative sequence and zero sequence components at the DC link capacitor of the non-isolated transformer. Conventionally the DC volt controller suppresses these components, but this paper has aimed to integrate this functionality within the VSG power loop. This is done using a droop control of the DC voltage against active power.

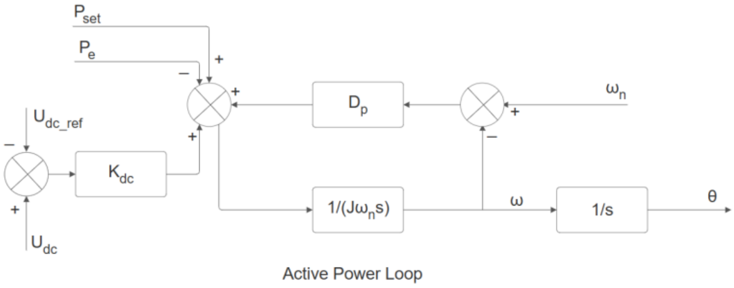

Figure 4: Improved power loop for DC link capacitor voltage control [9]

5.2 *Grid Side and Source-Load Voltage Control*

Controllers are implemented to nullify the influence of the negative and zero sequence grid side voltage on the grid side current. A quasi-proportional controller is used to balance the three-phase imbalance.

$$G_{i(s)} = k_{ip} + \frac{\{2k_{ir}\omega_{ir}s\}}{\{s^2 + 2\omega_{ir}s + \omega_0^2\}} \tag{5}$$

$$G_{v(s)} = k_{vp} + \frac{\{2k_{vr}\omega_{vr}s\}}{\{s^2 + 2\omega_{vr}s + \omega_0^2\}} \tag{6}$$

So initially control loop of grid side is shown in Figure 5. Here the grid voltage has an influence on the current. So, a feedforward controller G(s) is made after rearranging the control loop, so that H(s) can be made equal to zero.

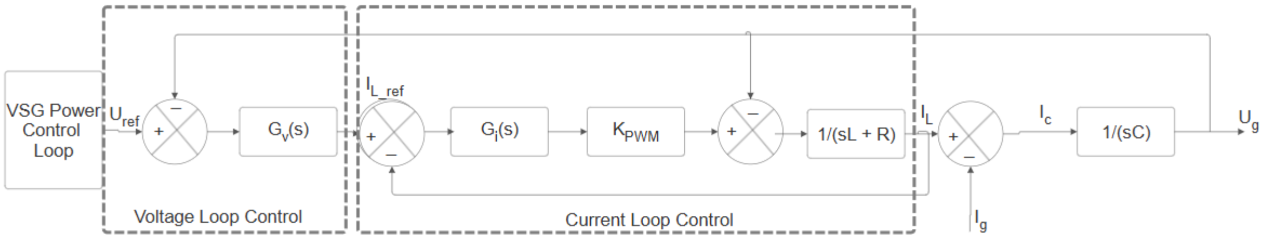

Figure 5: Control loop by only using quasi proportional controllers [9]

$$i_g = \frac{(G_{i(s)}K_{pwm})}{(sL + R + G_{i(s)}K_{pwm})} i_{Lref} - \left(\frac{H(s)}{(sL + R + G_{i(s)}K_{pwm})}\right) * u_g \tag{7}$$

Where,

$$H(s) = G(s)G_{i(s)}\, K_{\{pwm\}} - \left(s^2LC + sCR + sCG_{i(s)}K_{\{pwm\}} + 1\right) \tag{8}$$

But the grid side current can still be affected by Ug imbalance because of the relation

$$u_{\{ref\}} = \frac{\{\{i\}_{\{L,ref\}}\}}{\{G_{v(s)}\}} + u_g \tag{9}$$

Hence, to only use the positive sequence voltage of the grid voltage a phase locked loop is used, which is a second order controller called DSOGI-PLL. The complete voltage control diagram is shown in Figure 6 and the entire 3 phase control diagram for grid side is shown in Figure 7.

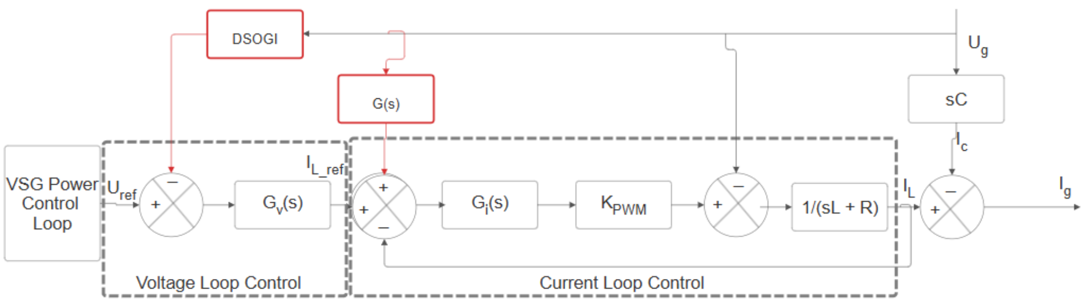

Figure 6: Voltage and Current control for grid voltage imbalance [9]

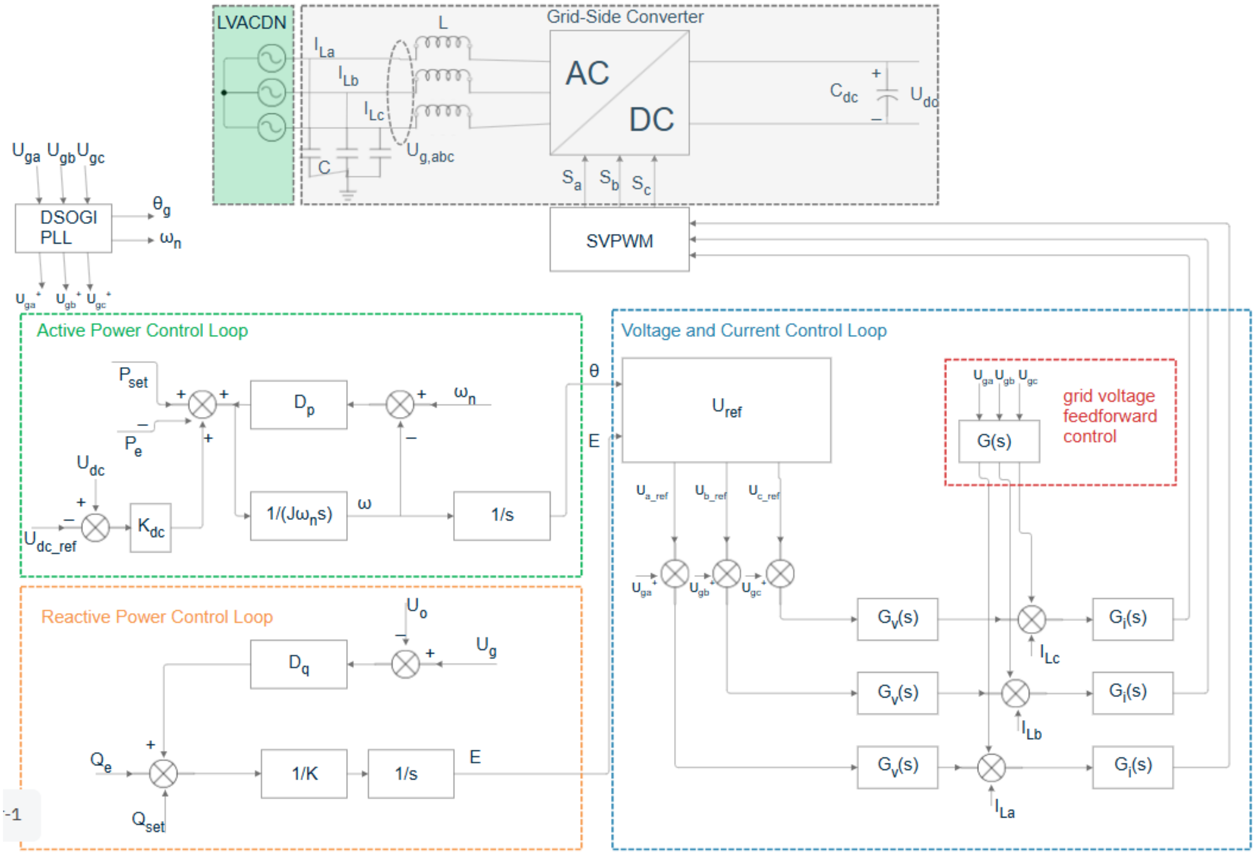

Figure 7: Improved control architecture for grid side voltage imbalance [9]

6. Implementations of control methods in ADNs [7]

5.1 *Dalrymple BESS*:

It is a 30 MW/ 8 MWh BESS, installed by ElectraNet in South Australia, which made it the one of the largest autonomous microgrids in islanded operation. It uses VSG technology, which provides synthetic inertia and high fault current so that more renewables can be integrated. When faults occur, power quality is not disturbed as the substation works with the local 91 MW wind and solar PV plant.

6.2 *Alinta Energy BESS*:

Implemented by ABB, a 30 MW VSG is used as spinning reserve for off-grid mining operations. The black starting feature of a GFMI is also utilised.

6.3 *Dersalloch Windfarm*:

This 69 MW wind farm of Siemens Gamesa turbines of the UK National Grid is the largest use case of GFMI control by a wind farm. It is used to control frequency and local voltage, before the island connects to the rest of the grid.

6.4 *AusNet Services GESS*:

A 1 MWA VSG based inverter integrates a 1 MVA diesel generator and a 1 MWh 1C lithium battery through a 3 MVA transformer. It is used to provide peak load support locally thus reducing upstream feeder requirements. In case of a fault the network goes into islanded mode and the GESS would supply load till fault is cleared, after which reconnection is done.

7. Research Directions [7]

1. Frequency Control
    1.1. It is important to study the interaction and performance of GFMIs under a mix of GFLIs and SM based generation?
    1.2. How many GFMIs can be used before the frequency regulation is not going to be affected much?
    1.3. How important is frequency regulation going to be in a fully IBR based network?
    1.4. What will be the solution when the regulating active and reactive power are not enough due to renewable intermittency?
    1.5. In case of droop control, what would be the best load sharing mechanism?

2. Voltage Regulation
    2.1. Conventionally voltage regulation is done by centralised power plants. In case of an ADN, voltage regulation services at the distribution level by many DERs. The way in which all of these voltage regulation devices work is a possible direction of research.
    2.2. The location of GFMIs to provide the best possible volt/var control determines the quality of voltage at all buses
    2.3. What would be the distribution of traditional QV droop control and communication based central control?

3. System Strength
    3.1. Overall, the VSG based methods are able to provide system wide performance even in weak distribution network conditions. However, it is important to find out which component (virtual inertia/ synthetic impedance/ damper windings/ flux model) of the VSG is playing a key role in the combined effect. This can help in finding out the sensitivity of the regulation to system strength and help improve stability.

4. Regulatory Framework
    4.1. GFMIs and control methods of ADNs is a relatively new technology
    4.2. It is imperative to instil confidence in grid operators and other stakeholders on the abilities of using this technology (mainly voltage and frequency regulation)
    4.3. The application should be gradual with demonstrations on microgrids first.
    4.4. It is essential to establish technical standards, commissioning procedures and other regulatory frameworks.

8. Conclusion

Active Distribution Networks are created due to the rise in high power loads (like electric vehicles) and the injection of power into the grid at the distribution level. The conventional protection systems are not designed to cater to the fast fluctuations in voltage and frequency, and the VVR systems in the grid are only designed to work over a few design cycles.
This literature review highlighted some of the prevalent methods to control voltage and frequency in ADNs. It can be done using optimisation of network-wide DERs with different objective functions and solution methods. Or new control architectures can be made. The most prevalent is the droop control, however it is not possible for it to provide the inertial and damping characteristics of a SM, which keeps the frequency within range in the conventional grid. So, VSG technology is used, which provides set points to the pulse width modulation of the IBR, so that it emulates the behaviour of a SM. This is done with various levels of complexity, of the SM model. It was found that the synchronverter is best when the application is in a weak grid (low short circuit index) which is the situation faced in high IBR penetration. A solution to the imbalance

in the distribution network was also discussed using droop control over the DC voltage of the solid state transformer, and a feedforward controller cascaded to the VSG based active and reactive power control. Examples of applications of these control methods were discussed where they are mostly applied to microgrids for small scale demonstrations. A few research directions were recognised in the domains of frequency and voltage control, system strength and the required involvement of regulatory committees to make the uses of AND control methods widespread in the certain IBR dominated future.

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