1 Introduction

1.1 Background of the study

Energiewende is a political statement initiated by the German national government with the objective of reducing the problems caused by the traditional energy systems in the area of ecological, social and health challenges. For many decades renewable energy (RE) has been seen as the preferred alternative to energy independence by every nation of the world [1]. *Energiewende* enhances the nation's economy by fully internalising the possible expenditure on the external costs. The ongoing war between Russia and Ukraine has further consolidated on the need to reduce energy imports, the effects on the German economy would have been much more devastating if not the massive progress that has been achieved in renewable energy integration.

According to [2], renewable energy productive capacity grew by 17 GW in 2023 to an aggregate of just below 170 GW. This implies a year-on-year growth of 12% which is largely dominated by both solar and wind. These two sources are in the forefront of replacing the conventional synchronous generation. Germany's growth in solar capacity in 2023 amounted to 14.1 GW, nearly double that in the year 2022. This was exclusively due to personalized ground-mounted and commercially installed rooftop solar capacity. Bavaria had the highest number of solar capacity in 2023, with 3.5 GW. At the end of 2023, installed solar capacity in Germany totalled 81.7 GW. This shows that 19 GW of fresh productive capacity will be required each year from now on if the goal of reaching 215 GW is to be met by the year 2030, please see Fig. 1.1 for the projection of solar power generation in Germany. In the wind energy technology, growth in onshore wind capacity in 2023 was 2.9 GW higher than in the previous year. Figure 1.2 comprises new capacity put into operation minus the capacity taken out of operation. Installed onshore wind capacity totalled 60.9 GW at the end of 2023. The target for 2030 is 115 GW of installed capacity. Germany will need 7.7 GW of new capacity each year to meet this target. Figure 1.2 illustrates the projection of wind energy installation (both for onshore and offshore).

The share of RE generation has risen from 24.7% to 54.9% of the net electricity generation between year 2013 and the year 2023, representing a significance boost and total commitment of German government in achieving self-sustenance in the energy sector.

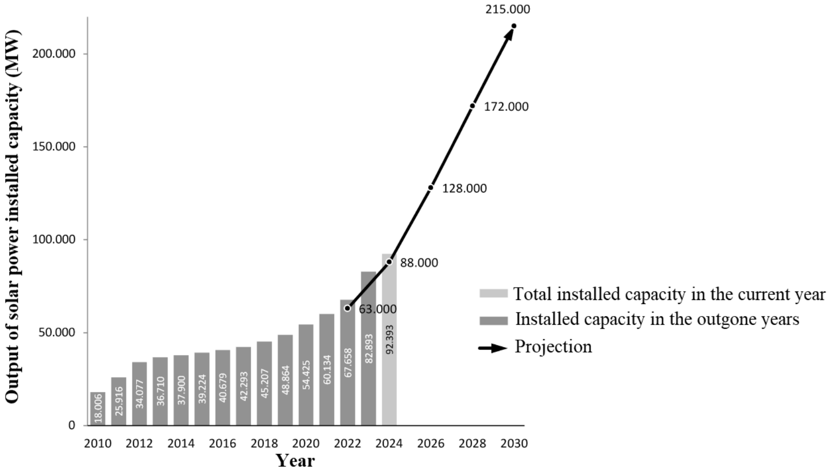

Figure 1.1. Solar power generation capacity in Germany [3]

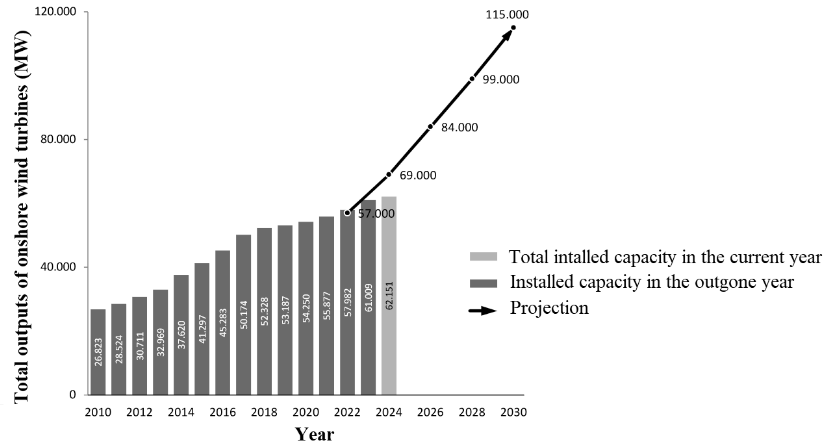

Figure 1.2. Onshore wind power generation capacity in Germany [3]

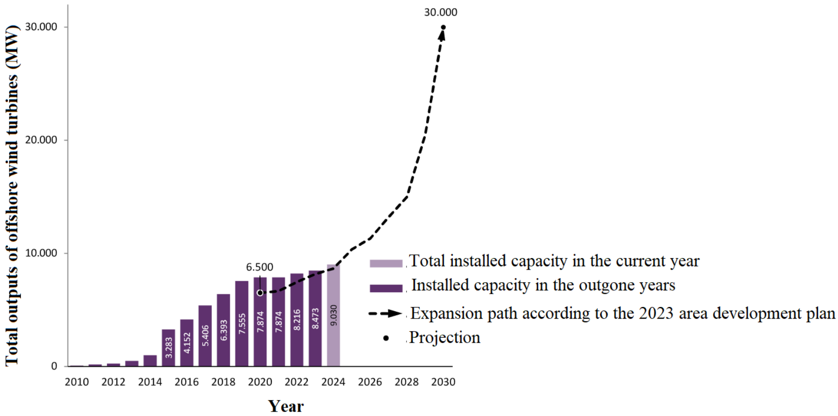

Figure 1.3. Offshore wind power generation capacity in Germany [3]

Fig. 1.4 illustrates the share of renewable energies in total net electricity generation between 1990 and 2023, the fell in the year 2021 was as a result of weather situation. It is evident from Figures 1.1-1.4 that renewable generation will continue to rise exponentially while it is expected that the fossil-fuel type will continue to be depleted year in year out. Before the introduction of RE into power grids, electromechanical synchronous machine (ESM) rules the domain of electrical power generation devices, they are characterized with the ability to provide excellent inertia and damping responses which guarantee stability of the grid frequency and regulate the power imbalance in the system [4, 5]. Due to the progressive development in renewable energy integration into the grid and the strong determination to have 100% inverter based generation (IBG) in the near future, there have been remarkable achievements in the control algorithm development for the interface power converters, the famous of which is the droop control [6].

Droop controls are decentralized control schemes and are suitable for both grid and isolated operations [7]. In the grid connected inverter, they are implemented to regulate the exchange of active and reactive power with the utility, in order to keep the grid voltage amplitude and frequency within a normal range. In the autonomous mode, the droop control-based inverters can provide voltage support and share load power according to their power ratings. . They do not require communication control lines, they are reliable and highly responsive, and are very suitable in both grid and isolated operations [7]. Despite the wide acceptability of droop control, it suffers from inertia issues and thus cannot ensure system frequency stability during disturbances. Inadequate reactive power sharing, sensitivity to faults and poor voltage regulations are other issues associated with droop control microgrids [8-10].

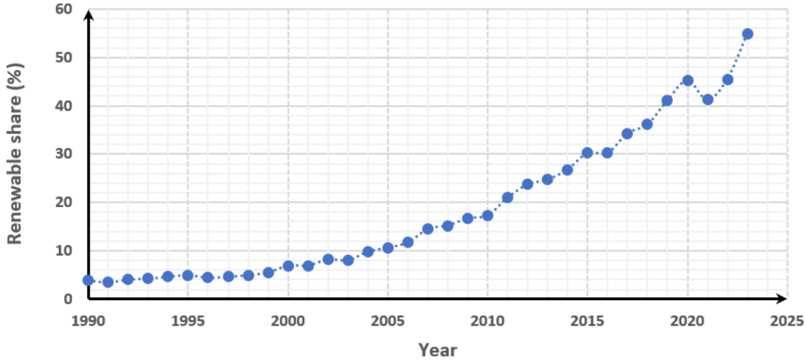

Figure 1.4. Share of renewable energies in total net electricity generation [11]

An electrical power system with zero inertia is unstable, experiences power quality issues, and is vulnerable to blackouts [12]. If there is a change in load demand, then the system frequency also tends to change. The frequency fluctuations can be mitigated by the presence of sufficient rotating masses on the grid, which act like a shock absorber. Therefore, the increasing penetration level of distributed energy resources (DER) will have enormous effects on the dynamic response and power system stability [13]. Examples of the most recent power system instability scenarios are those of South Australian Black out which occurred on the 28th of September, 2016 [14] and that of the European continental power failure that occurred on the 8th of January, 2021 [15]. Heterogeneous frequency traces seen as a result of the European continental power failure are shown in Fig. 1.5.

In order to provide ancillary services needed by the distributed generators (DGs) for a stable operation of power systems, **Vi**rtual **S**ynchronous **Ma**chines (VISMA) technology, also called **V**irtual **S**ynchronous **G**enerator (VSG) [16] has been proposed in the literature as a suitable idea for controlling inverters by mimicking the behaviour of conventional ESM [17]. Generally, VISMA have the capability to reproduce the static and dynamic properties of ESM on a power electronic interface converter faster. VISMA is a special controlled inverter that is able to integrate different forms of RE sources into the grid, this is shown by the elementary structure shown in Fig. 1.6.

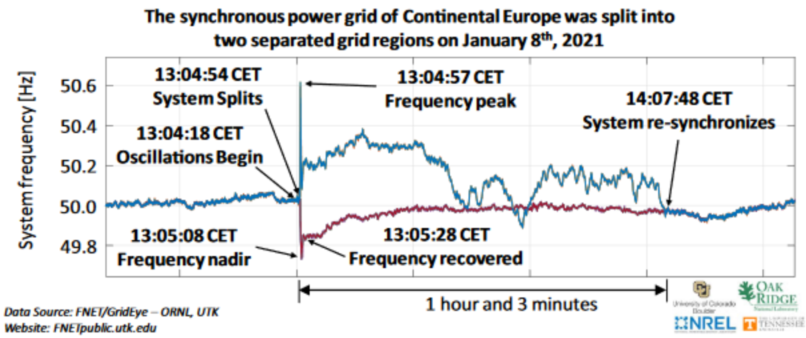

Figure 1.5. Frequency traces of the European synchronized continental power network failure [15]

Some of the important features of VISMA are i) ability to initiate inertia response to resist change in grid frequency ii) ability to effectively damp out rotor oscillations during disturbances, thereby improving transient stability iii) ability to independently and bidirectionally control the active and reactive power at the grid. The fundamental concept of VISMA technology is the simulation of an ESM on the basis of an inverter in combination with an energy storage unit and a microcomputing unit for determining the electrical, magnetic and mechanical machine parameters using a mathematical representation of synchronous generator in real time.

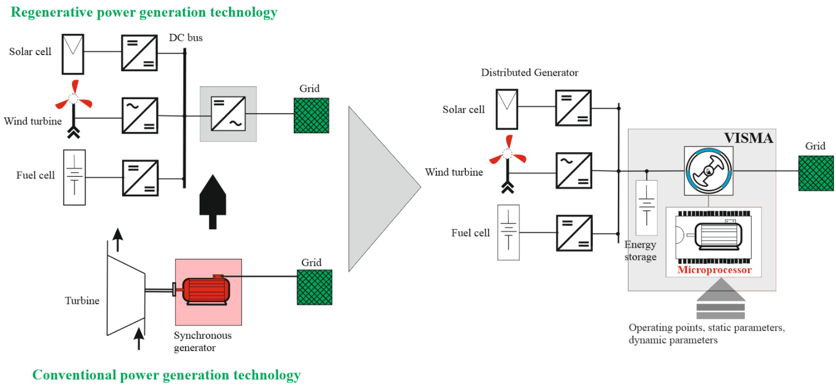

Figure 1.6. Basic structure of VISMA [18]

1.2 Power system stability category

The evolution of smart grids over the past two decades has posed several technical challenges to the power system operations. New instability scenarios now appear in the power system, and according to reports, the most prevalent are the low-frequency oscillations that occur due

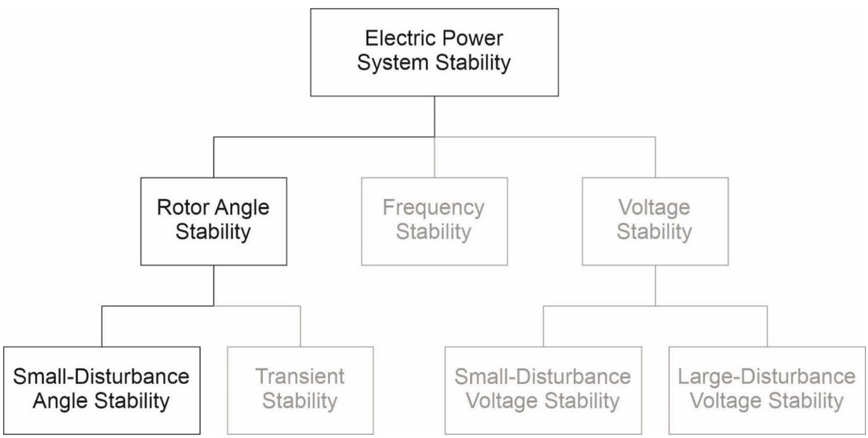

Figure 1.7. Classifications of power system stability [19]

to weak grid. Depending on the network configuration, circumstances surrounding the system operation, nature of disturbances and time lapse of fault, varieties of instabilities may evolve. Power system stability is basically categorized into rotor angle stability, frequency stability and voltage stability, [16, 20-24], and it is schematically represented in Fig. 1.7. A detailed explanation of each category and sub-category of power system stability is provided in Ref. [19].

1.3 Motivation and research objectives

Due to the deep structural transformation of the global energy sector from the well-known centralized generation to now decarbonized, digitalized and decentralized power systems, it is necessary that power equilibrium is maintained between generation and load if the grid frequency is to be kept within the acceptable stability margins. When the grid voltage is affected by a perturbation, such as imbalances, transients, or harmonics, which is normal in power grids, conventional grid inverters find it difficult to remain appropriately synchronized with the grid voltage [25]. Power mismatches can lead to uncontrolled power flows which may result in severe fluctuations in frequency and voltage amplitude, thereby negatively impacting grid stability [8, 10]. Grid stability is a paramount issue in power system operations, it has a crucial role to ensuring a safe, reliable and optimal operation of high order multivariable modern power system whose dynamic response is dictated by several components with distinctive properties. To allow seamless deployment of inverter-based generation and meet stringent demand of the power system operators (PSO), the overall performance of the electrical power system needs to be enhanced by providing solutions to dynamic stability and control challenges. The deployment of novel technologies and controls has led to several questions being asked regarding the microgrid responses to perturbations [13, 26]. In a multi-VISMA (*n*-VISMA) microgrid, the ability to re-establish balance between the opposing forces is ensured by the rotor angle stability of each VISMA. Rotor angle stability is the ability of the VISMA to remain in synchronism with the network after being subjected to disturbance caused by torque imbalances in the system. Stable synchronized operation of VISMA rotor angles is thus a critical stability problem for a secured microgrid. According to Fig. 1.7, angle stability is categorized into a small-disturbance and large disturbance stability. Stability analysis in traditional power grids is long-established using the classical models of ESM, speed-governors and the excitation systems of different orders designed to solve a specific kind of problem. In the modern inverter-based power grid with high level of distributed energy resources, there is no specific analytical standard because of different control strategies/synthesis which are continuously evolving. Different VSGs require different computational models to understand the interactions between different units in the microgrid system.

This dissertation aims to consider a special case of n-VISMA microgrid in autonomous operation with a specific focus on *small-disturbance rotor angle stability.* If the rotor oscillation as a result of a perturbation is not resolved in due time, it can lead to severe damage of the power plant [27]. For traditional power systems, synchronization dominated by rotor motions occurs in a physical sense. However, in the VISMA based microgrid, synchronization between VISMAs corresponds to their virtual rotor vectors and it is necessary that the transient induced in the network following a small perturbation is damped out such that their kinetic energy is dissipated within a relatively short period. All the VISMAs in the network must at the same time regain their identical speed. In a network of n-VISMA, a synchronous state is described in equation (1.1) [28].

$$\dot{\delta}_1 = \dot{\delta}_2 \ldots.\ldots\ldots. = \dot{\delta}_n = w_s \qquad (1.1)$$

Where δ, is the load angle and w_s, is the synchronous speed.

1.4 Research contribution

Since 2007, different topologies of VSG controls have been proposed [29] and many are still continuously evolving. Due to these different control strategies, small-signal stability analysis techniques also differ. After extensive review of literature, it was found that most of the stability analysis scenarios of VSG control converters are based on a single machine grid-connected system or sometimes on multimachine model under mixed configurations involving both synchronous generators and inverted systems [30, 31]. Studies of general multi-VSG systems with 100% power electronic devices are rare. In addition, not much work has been done on the stability analysis (either small-signal or large signal) of VISMA model from IEE TU-Clausthal, Germany, and the most recent work by [32, 33] was carried out at system level. The traditional VISMA model presented in [29] does not incorporate outer power controllers, the active and reactive power regulations were respectively achieved by setting the model parameters virtual torque and virtual excitation as it was similarly done in [34]. Also, most of the stability analytical model of VSG control schemes are cumbersome and computationally intensive like that developed by [35] for a single machine which may not be easily realizable for multimachine analysis. Those models that are simpler are not suitable for operation in autonomous mode. The contributions of this thesis are summarized as follows:

1. Full flexibility of operation is achieved by adding a two-loop power controller localized to each VISMA on the grid. The automatic voltage regulator (AVR) in closed loop form ensures that the adjusted pole wheel voltage based on system operating conditions (E_{po}^{*}) is kept equal to the VISMA voltage set-point (E_0). The control structure makes it possible to set the respective ancillary services in a desired manner as shown in Fig. 6.1. In the multi-VISMA microgrid presented, each VISMA unit is designed to have an independent control so that fundamental, active and reactive powers can be shared based on individualized static droop coefficients.
2. New approach into small-signal synchronous stability of multi-VISMA microgrid system in the absence of an infinitely swing bus.
3. A novel closed-form steady-state, fundamental-frequency model for an autonomous/islanded VISMA microgrid using the concept of *virtual swing bus* was developed to obtain the stationary operating points of all the dynamic nodes in the system. This proposed concept employs the use of constant amplitude of virtual excitation and virtual torque localized to each VISMA unlike the droop bus approach that uses active and reactive power coefficients as major constant control parameters.
4. Eigenvalues and parametric sensitivities stability analysis of multi-VISMA system.

1.5 Thesis outline

This dissertation is structured as follows:

Chapter 1 presents the general background on the study, motivation and objectives of the research and major contributions of the study. Chapter 2 provides a review about different kinds of grid inertia control system available in literature. A more comprehensive analytical detail regarding the sub-units of abc simplified VISMA control technology invented by TU-Clausthal, Germany is also presented. Per-unitization of analytical variables is also highlighted. In Chapter 3, relevant mathematical tools necessary for the stability analysis of modern power systems are presented with special focus on selective modal analysis, transition matrix and linearized small-signal model. Chapter 4 discusses a closed-form steady-state, fundamental-frequency model for islanded/autonomous VISMA microgrid using the concept of virtual swing bus. In Chapter 5, linearized small-signal rotor angle stability of uncontrolled multi-VISMAs in autonomous operation is presented while Chapter 6 investigates rotor angle stability of multi-virtual synchronous machines with an outer active power loop controller (PLC). A summary of the key findings and suggested recommendations follows in Chapter 7.