Control Strategies and Prospects for Flexible Multi-State Switch in Intelligent Distribution Network

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August 31, 2023

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***Abstract*—Renewable energy generation is friendly to the environment and increases rapidly. However, its random output impacts the power quality and stability of the traditional distribution network significantly, including negative sequence current, voltage drop, and power disturbance. A flexible multi-state switch (FMS) can improve the flexibility and security of distribution network operation. It provides a new technical solution for a series of problems caused by the high proportion of renewable energy access to distributed generation. In this paper, the principle and topology of FMS are briefly described. Aiming for the power quality of the distribution network, the control strategies of FMS in unbalanced current regulation, voltage fluctuation suppression, as well as power flow dispatch among ports and feeders are reviewed. The critical control strategies are analyzed and compared. Furthermore, the prospective FMS applications in intelligent distribution networks with renewable energy are discussed.**

Keywords—flexible multi-state switch, power quality, control strategy, intelligent distribution network.

I. INTRODUCTION

With the increasing shortage of traditional fossil energy and global climate change, renewable energy power generation is improving fast [1]. However, conventional power grids are generally closed-loop designs and open-loop operations [2]. The distributed renewable energy with randomness and uncertainty brings challenges to power regulation in the traditional power grids. For example, renewable energy power generation, such as wind power and photovoltaics, will fluctuate with the change in natural environmental factors, which is hard to maintain constant output and bring disadvantages to power flow scheduling. Besides, with access to renewable energy, the short-circuit currents turn larger and shorten the life of the equipment. At the same time, due to the unpredictability of the renewable energy power supply, it will cause power quality problems such as voltage over-limit. The issue of renewable energy access has seriously endangered the power supply reliability of the distribution network [3].

To solve these problems to realize the flexible control of power flow in the distribution network, many new flexible devices have been proposed in recent years [4]. The flexible multi-state switch is a new type of flexible interconnection equipment, which can meet the consumption of distributed energy in a smart grid and improve the reliability, flexibility, and power quality of the power supply[5]. Therefore, the power quality compensation control of flexible multi-state switches in distribution networks has become a research hotspot.

In this paper, the topology of flexible multi-state switches is summarized, and various control strategies of flexible multi-state switches for power quality compensation are analyzed and compared.

II. TOPOLOGIES OF FMS

As a new type of flexible distribution equipment, FMS is composed of fully controlled power electronic devices, which can be realized by back-to-back voltage source converter (VSC), unified power flow controller (UPFC), and static synchronous series compensator (SSSC) [6]. The topology of FMS is mainly divided into two-port and multi-port. The typical two-port topology of FMS is shown in Fig.1.

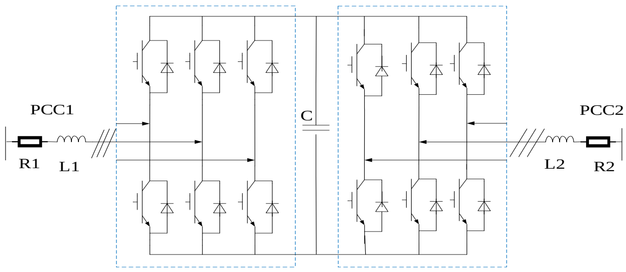

Fig. 1. Illustration of two-port FMS

In [7], the structure of a two-port FMS is introduced. It is composed of two VSCs connected in parallel through the DC side, which has the function of controlling the amplitude and phase of VSC output voltage. L is a converter reactor, which is the link between the converter and the AC power supply for energy exchange, and has a filtering function. C is a DC-side capacitor, which plays the role of DC voltage support, buffering the inrush current when the bridge arm is turned off, and reducing the DC-side harmonics. Therefore, it can be used to achieve flexible control of active and reactive power between interconnected feeders. In addition, in the case of system failure, the short-circuit current can be suppressed by controlling the converter to ensure the uninterrupted power supply of the load [2].

The two-port back-to-back FMS is widely used in medium and low-voltage distribution systems [8]. The loss of a small number of FMS in the entire power system is negligible [9]. It also has the characteristics of simple topology and low cost [10]. However, it is precisely because of these characteristics that the voltage resistance of the switch tube of the two-port

The research of this paper was funded by the "The Basic Ability Enhancement Program for Young and Middle-aged Teachers of Guangxi (project No.: 2023KY1243)" project.

back-to-back FMS has certain limitations, and when the two ports fail, the system cannot be transferred through the FMS device [11].

In addition to the two-port FMS, the three-port FMS is also widely used in the flexible interconnected distribution environment. The three-port FMS topology[12] is shown in Fig.2.

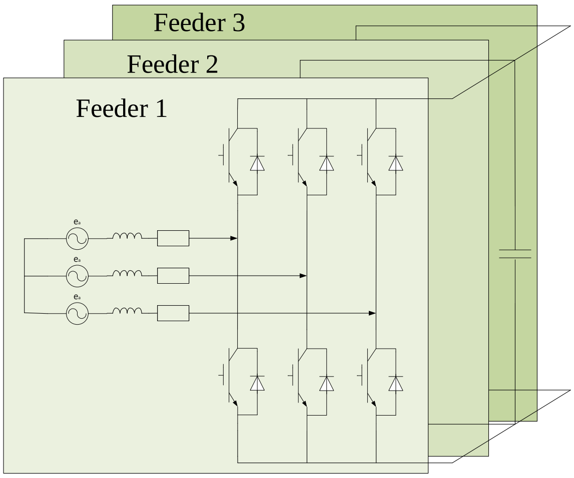

Fig. 2. Illustration of three-port FMS

The three-port FMS topology is composed of three voltage source converters (VSC1, VSC2, VSC3). The structure of the three VSCs is the same and symmetrical, and the middle is connected by capacitors. The capacitor is mainly to provide voltage support for the VSC and reduce the DC side harmonics, and the inductance L in the VSC is to play a filtering role.

Taking VSC1, one of the three ports, as the research object, if a single L-inductance filter is used, the continuous mathematical model of the AC side in the three-phase stationary ABC coordinate system is established:

$$\begin{cases} E_{j1} - \left(i_{j1} + i_{Rj1}\right) R_{g1} - L_1 \dfrac{di_{j1}}{dt} = U_{j1} \\ 0 + R_1 i_{Rj1} = U_{j1} + L_1 \dfrac{di_{j1}}{dt} \end{cases} \tag{1}$$

In the ABC three-phase stationary coordinate system, after the Clark transformation of the three control variables, the continuous mathematical model is mapped to the αβ two-phase stationary coordinate [13]:

$$\left(1+\frac{R_{g1}}{R_1}\right) L_1 \frac{d}{dt}\begin{bmatrix} i_{\alpha 1} \\ i_{\beta 1} \end{bmatrix} = \begin{bmatrix} E_{\alpha 1} \\ E_{\beta 1} \end{bmatrix} - \left(1+\frac{R_{g1}}{R_1}\right) u_{dc} \begin{bmatrix} m_{\alpha 1} \\ m_{\beta 1} \end{bmatrix} - R_{g1} \begin{bmatrix} i_{\alpha 1} \\ i_{\beta 1} \end{bmatrix} \tag{2}$$

Under normal circumstances, the three-port FMS cannot work in the same mode at the same time, generally one or two in the inverter mode, the other port in the rectifier mode; or one or two in the rectifier mode, the other in the inverter mode [14]. Under normal operation, the loss of P_{loss} of the three-port operation of FMS will be less than 6 % of the rated power [15].

The three-port FMS has the ability of power flow control, can carry out subjective rapid control, can achieve rapid recovery of power supply after fault, and can also carry out feeder energy transfer and certain DC fault isolation abilities [16]. However, the strong function of FMS also makes the cost of three-port FMS higher than that of two-port FMS, and the cost performance of construction is not high. In [10], various three-port FMS topologies are introduced, and the topology with the highest cost performance can be selected according to different applications. At present, three-port FMS is mainly used in medium voltage distribution networks [16]. According to the application of three-port FMS, different control strategies are proposed to optimize the application of three-port FMS, which still has a good application prospect.

The access of typical multi-port FMS in the distribution network[17] is shown in Fig.3.

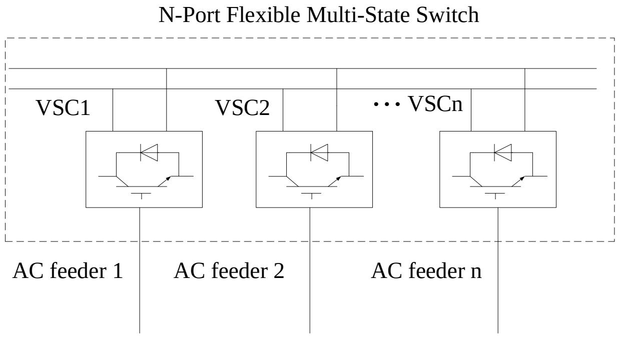

Fig. 3. Illustration of multi-port FMS

Because the multi-port FMS can realize the mutual support between multiple feeders, it has more advantages in terms of adjustment ability and operation reliability [18]. At the same time, because of its multi-port structure, the multi-port FMS has more optimization methods, and according to its specific application scenarios, different access topologies can be constructed.

III. CURRENT REGULATION STRATEGY BASED ON FMS

A. *Zero-sequence Current*

With the continuous development of power electronics technology and the increasing number of unbalanced loads, the degree of three-phase load imbalance is becoming more and more serious, and the zero-sequence current is too large, which seriously affects the life and safety of distribution network equipment [19]. Therefore, in the normal operation of the three-phase power system, the zero-sequence current should be controlled at a lower level. To accurately detect, analyze and process these zero-sequence current components, [20] studies the AC to DC zero-sequence suppression and DC to AC zero-sequence suppression. The two joint control strategies can effectively suppress the transmission of zero-sequence fluctuations on the AC or DC side to the normal supply area, and can effectively reduce the additional investment cost caused by the DC voltage rise of the voltage source converter, but this method does not have insufficient research on the topology. Therefore, [21] combines the research on the topology structure and designs a zero-sequence component suppression strategy through an asymmetric FMS topology structure, which realizes the zero-sequence suppression of unbalanced current. [22] proposed is more optimized in topology and control methods. The improved scheme of the MMC sub-module control strategy and the zero-sequence control loop based on the PR controller are studied. The control strategy is shown in Fig.4.

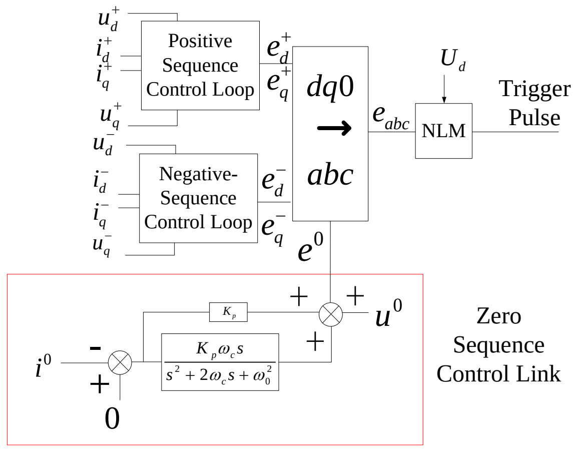

Fig. 4. MMC sub-module optimization control strategy

B. *Harmonic Pollution*

With the increasing proportion of distributed power access to the distribution network, the problems of harmonic amplification and harmonic resonance caused by the harmonic superposition effect of a large number of distributed power sources are becoming more and more serious and complicated [23]. To strengthen the control of harmonics, [24] proposed a ring-type FMS access method, which uses a closed-loop operation method to achieve harmonic suppression through back-to-back converters, but the control structure of this method is more complicated. Therefore, the structure of [25] is fully simplified, and a traditional model predictive control based on three vectors is studied to increase the number of voltage vectors in the sampling time, to effectively reduce the harmonic current, and have better current stability. However, the THD ability of this method is insufficient. To improve the THD capability of the system, [26] proposed a FMS mathematical model of unbalanced and nonlinear loads, and a reference current detection method based on the instantaneous reactive power theory. The principle is shown in Fig. 5.

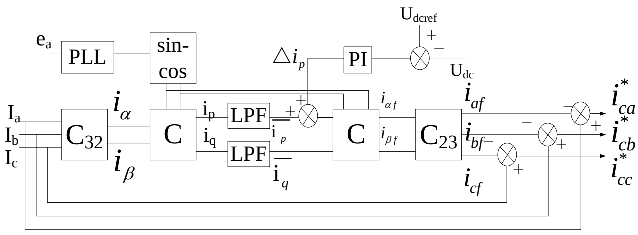

Fig. 5. Reference current detection method

This method is used to detect and suppress the harmonic current components in the load unbalanced current, and the output current is adjusted by the PI controller. [27] proposed a positive and negative sequence double-loop control strategy. The negative sequence uses a resonant controller to suppress the resonant current. The structure of the strategy is simpler and the THD capability is stronger. The above methods can effectively improve power quality and improve system stability, but they have not been studied and considered in detail from the economic level.

IV. VOLTAGE REGULATION STRATEGY BASED ON FMS

A. *Voltage Distribution*

The integration of renewable energy into the power grid makes the traditional distribution network change from one-way radiation to a multi-point network structure, and the problems of node voltage fluctuation, network loss, and reliable power supply are constantly highlighted [28]. Therefore, it is particularly important to ensure that the voltage of each part is within the allowable range to meet the needs of users. To suppress the voltage fluctuation of each node, [29] proposed a voltage adaptive control strategy based on the improved discrete consensus algorithm. The voltage adaptive function is as follows:

$$\min \sum_{i_v}^{N_v} \left(U_{i_v} - U_{i_v}^{d} \right)^2 \tag{3}$$

[30] proposed a model-free adaptive control strategy for nonlinear systems. This method changes with the fluctuation of renewable energy on the required nodes, and the actual voltage curve can track the expected voltage curve. This strategy has good applicability.[31] proposed the optimization and improvement of voltage distribution by using back-to-back synchronizers to loop two adjacent networks at both ends. The above methods are more biased towards the optimization and improvement of the algorithm, ignoring various situations in practical applications. To better adapt to the practical application, [32] proposed the voltage fluctuation suppression strategy of the distribution network based on FMS to control FMS in real time and realize the balance of node voltage distribution in the distribution network. The reactive power coordinated control optimization model proposed in [33] ensures the power quality of the user's electricity demand and the voltage distribution level of the network through reactive power compensation. By studying the power supply capacity evaluation model of smart distribution networks with FMS, [34] proposed considered a variety of operating constraints and scenarios and optimized the voltage distribution of each node.

B. *Voltage Stability*

The large number of distributed power access has a great impact on the voltage deviation and voltage stability of the distribution network [35]. To analyze and adjust the voltage of the distribution network system to ensure that the voltage of each part is within the allowable range, [36] proposed a fuzzy active disturbance rejection control FMS control strategy, which is combined with the linear active disturbance rejection control (LADRC) controller. The control structure is shown in Fig.6.

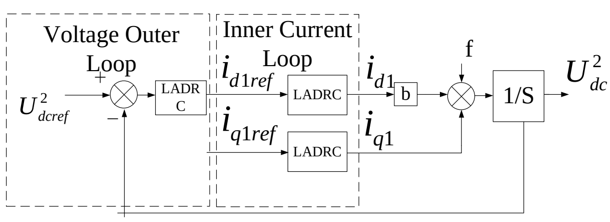

Fig. 6. DC voltage control based on double-loop LADRC

This method makes the system have stronger anti-interference ability. Through the study of three-port FMS, the anti-interference ability of the system is improved so that the

DC side voltage is more stable. [37] proposed a voltage feedforward control link to suppress the disturbance of the AC side voltage and improved the stability of the DC voltage by improving the virtual inertia control. The above methods are biased towards the improvement of algorithms or control methods and lack research on system hardware. Therefore, [38] designed an improved voltage compensator based on synovial control and combined it with a nonlinear disturbance observer to improve the suppression of voltage deviation information collection and improve the accuracy of the control strategy, the method also designed a voltage feedforward control link to suppress the disturbance of the AC side voltage, and improved the stability of the DC voltage by improving the virtual inertia control. The above methods are biased towards the improvement of algorithms or control methods and lack research on system hardware. Therefore, [20] designed an improved voltage compensator based on synovial control and combined it with a nonlinear disturbance observer to improve the suppression of voltage deviation information collection and improve the accuracy of the control strategy.

V. Power Flow Dispatch Based on FMS

A. Power Flow among Ports

As one of the most popular converter topologies in high-voltage applications, modular multilevel converter (MMC) has the characteristics of easy expansion, high power quality, and controllable power factor [39]. Aiming at the power regulation problem of MMC, an improved droop control strategy is designed by introducing the FMS method in [40],[41], which is shown in Fig.7.

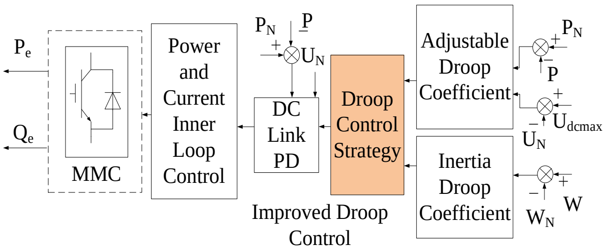

Fig. 7. The control block of improved droop control

According to the droop coefficient, the active power is adjusted in real-time. This method has better accommodation ability, but the response speed is slightly worse. In [42], the sensitivity coefficients of active and reactive power of each node voltage are obtained by applying power disturbance to FMS, and the active power balance and reactive power compensation of each port converter are realized. This method improves the system's response speed, but the absorptive capacity is insufficient. [43] proposed an improved coordinated control strategy. By introducing a voltage change follower in the constant power outer loop controller, multiple converters participate in power regulation at the same time, avoiding the power of a single converter, and improving the consumption ability and response speed, but losing a certain stability.

B. Power Flow among Feeders

With the large-scale access to distributed energy, the randomness of its output makes it impossible for the traditional distribution network to achieve precise control, resulting in inflexible power transmission capacity between feeders, resulting in a large amount of renewable energy being wasted[44]. Active and reactive power regulation of feeders through FMS can maintain voltage stability, optimize power distribution and improve power flow distribution in the power system. To study active and reactive power regulation schemes suitable for different scenarios, [45] considered a control strategy for the power interaction of the DC microgrid. The AC and DC ports are controlled by virtual motors and feeder power regulation is realized by the energy storage unit with FMS. [46] proposed a coordinated control method for multiple ports of FMS. Through the double-layer algorithm of the reference point optimization layer and slope optimization layer, feeder power sharing and network loss reduction are realized. [47] proposed the mechanism of power interaction between FMS and feeders on both sides and designed a feeder interconnection control strategy to realize reactive power compensation of feeders through a double closed-loop control strategy. The above articles focus on the flexibility and regulation ability of the control algorithm and lack the analysis and consideration of the hardware structure and economic problems. Based on the access mode and topology structure of FMS, [48] proposed a new composite control strategy, which can adjust the power of multiple feeders and has good economic benefits. [49] proposed a three-port triangular AC-AC converter, which not only reduces the investment cost but also uses the current regulation characteristics of the third phase arm to not only meet the power demand of the output feeder but also meet the flexible distribution of the input feeder power.

VI. Conclusion and Prospects

The integration of intelligent distribution networks with renewable energy generation is becoming a tendency around the world. But the uncertainty and intermittence of renewable energy generation have brought great challenges to the power system. Due to multi-loop states and flexible dispatching capabilities, FMS provides a series of solutions to solve these problems. Moreover, FMS can improve power quality, power system operation efficiency, as well as stability and reliability of the power system. Through the overview of different control strategies in this paper, the comparison can be listed as TABLE I, and the conclusions can be presented as follows.

TABLE I. Comparisons among Control Strategies for FMS

For Harmonic Pollution				
Item	[24]	[25]	[26]	[27]
Suppress Performance	*	**	***	***
Control Complexity	***	*	***	**
For Voltage Stability				
Item	[36]	[37]	[38]	
Stability Performance	*	*	***	
Response Speed	**	*	**	
Control Complexity	***	*	**	
For Power Flow Dispatch				
Item	[40],[41]	[42]	[43]	
Stability Performance	*	***	**	
Response Speed	**	*	*	
Capacity Range	**	*	**	

* means poor, ** means medium and *** means good.

1) After FMS compensation, the zero-sequence current, the harmonic pollutions, and the neutral voltage rise all can be suppressed. These current compensation methods improve the power quality and decrease the risk of equipment damage. It denotes that the reliability of the equipment and the stability

of the system is improved, as well as the cost of repairing voltage rise and equipment loss are reduced.

2) FMS can suppress voltage fluctuation, reduce the impact of unstable voltage on the devices, and prevent voltage from exceeding the limit. It denoted that the voltage distribution can be re-dispatched controllably, and the anti-interference ability of the power system can be improved. Thus, the failure rate and line loss both can be reduced.

3) Depending on suitable power control methods, FMS can balance the power flow among different feeders and increase the power factor at each port. By improving the distribution of feeder power flow, it can better adapt to the impact of unpredictable volatility caused by renewable energy and load consumption. Consequently, the intelligent distribution network with FMS can flexibly respond to various risks.

However, the installation and maintenance cost of FMS is still high. It is the main obstacle of FMS in industrial applications. With the development of semiconductor materials and high-power device packaging technology, the large-scale promotion of FMS in power systems is expective. Limited by its rating capacity and voltage level, FMS is investigated in the distribution network. In the future, through the advanced design of its topology and the optimization of access mode and parameters, multi-terminal, large-capacity, and high-voltage FMS access can be realized. FMS will become an important participant at a wider grid level. Meanwhile, the integration of artificial intelligence technologies and power quality compensation controls brings a great chance, and FMS has the potential to achieve multi-functional compatibility with lower costs.

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