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A review of magnetically controlled shunt reactor for power quality improvement with renewable energy applications

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A R T I C L E I N F O

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A B S T R A C T

Renewable energy sources are widely available on Earth; hence they have attracted much interest in both research and practical applications. In the large scale renewable energy system, power quality into the grid, especially harmonics and flicker, impacts on grid system significantly. In recent years, magnetically controlled shunt reactors (MCSRs) have been widely used to solve the problems of the power quality caused a failure or malfunction of the end-user equipment. MCSR can simplify the system reactive power and voltage control in the super / special high-voltage power grid, suppress power frequency and operation over voltage, eliminating generator self excitation, dynamically compensate charging the power in a transmission line, suppress the secondary arc current, damping system resonance and so on, which can meet the various needs of the system, it has a very broad application prospects. This paper presents a comprehensive review of MCSR configurations, the control strategies, the selection of components, other related economic and technical considerations, and their selection for specific applications. It is aimed at providing a broad perspective on the status of MCSR technology to the researchers and the application engineers dealing with power quality issues. A list of more than 130 research publications on the subject is also appended for a quick reference.

1. Introduction

With the development of technology, electric utilities and usage of electric power are increased. The majority part of energy demand is provided by fossil fuels. However, fossil fuels are finite resources and will eventually decrease. Due to this condition, they become too expensive or too environmentally damaging to retrieve. In the recent years, renewable energy in power generation has been emerging as an alternative energy source to mitigate the disadvantages of fossil fuels. Renewable energy sources are widely available on Earth; hence they have attracted much interest in both research and practical applications. In the large scale renewable energy system, power quality into the grid, especially harmonics and flicker, impacts on grid system significantly.

Nowadays, electric power quality (PQ) problems are vital issue due to the increase in the number of the loads sensitive to power disturbances [1–5]. The problems of the power quality such as voltage, current or frequency deviation cause a failure or malfunction of end-user equipment [6–9]. However, power quality problems are not restricted to harmonic distortion. The standard IEEE 1159 classified various electromagnetic phenomena in the power system voltage (which are related to power quality problems), namely: impulses, oscillations, sags, swells, interruptions, under voltages, over voltages, DC offsets, harmonics, inter harmonics, notches, noises, flickers and frequency variations [3]. Meanwhile, many precise instruments and equipments in the various fields of the modern information technology, microelectronic technology and numerical control machine have a higher requirement for power quality. Dynamic reactive power compensation and harmonic elimination methods (or power quality controller) have attracted more and more attentions [10]. Many approaches have been proposed to solve this problem. For reactive power compensation, conventional rotating synchronous condensers as well as fixed and mechanically switched capacitors or inductors have been used for reactive power compensation [11–13]. However, in recent years, the static var compensator (SVC) based on thyristor and the static synchronous compensator based on self-commutated converters

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have been widely used for dynamic reactive power compensation. SVC [14–31] employs thyristor-switched capacitors and thyristor-controlled reactors (TCRs) to provide or absorb the required reactive power. In order to substitute the TCRs [32–42], some variable reactors have been proposed. The current technologies of a variable reactor include tapped the coils, the adjustable air gaps, the controllable reactors of the transformer type (CRT) [43–53], the saturable reactor (SR) [54–70], and the variable reactor based on a virtual air gap [71,72]. The SR can be sorted into two types: the magnetically controlled reactor and the orthogonal-flux controllable reactor. The difference between them is that in the former, DC and AC flux are in the same direction; in the latter DC and AC flux are orthogonal [73]. DC and AC flux will be explained in the working principle of MCSR [74–133].

The magnetically controlled shunt reactor (MCSR), as an important component of the controlled shunt reactor family [132,133] with the advantages of continuously adjustable capacity, low harmonic and excellent control characteristics, is widely used in EHV/UHV networks for the reactive power control. They have lots of advantages against the fixed reactors and TCR shown in below:

- to control the maintenance of the voltage or any other operation parameter without using circuit breakers in automatic switching systems;
- to decrease an active power losses in networks and to improve their operational reliability by reducing the number of switching in on-load tap-changing transformers;
- to enlarge a small signal stability margin;
- to improve a power system damping;
- to minimize using of the synchronous generators as a controlled sources of the reactive power;
- to have flexibility [74–77].

MCSR is worked as a power quality device in literature. MCSR is generally used to suppress overvoltage [78–92], mitigate secondary arc current [75,80,93,94], obtain voltage stabilization [73,76,78,79,92,95–98] and reactive power compensation [73,76,77,79,82,83,85,86,89,92,95–109], mitigate voltage/current harmonics [80,83,90,96,102,110] in EHV/UHV transmission lines. It seems that MCSR is a multi-functional device to increase power quality [76].

This paper aims at presenting a comprehensive survey on the subject of MCSRs. More than 130 publications [1–137] are reviewed and classified in sub categories. The first part is on the power rating and applications, while the second category is on the power circuit configuration and connections. The third category of publications is on the system parameters to be compensated (e.g. current harmonics, power factor, unbalanced three-phase system etc.). The four category includes the control techniques employed. The fifth category of publications is on the technique used for estimating the reference current/voltage. The final category of publications is on the selection of MCSR for specific applications. However, some publications belong to more than one category and have been classified based on their dominant contribution. This paper is presented in four parts. Starting with an introduction, the subsequent sections cover the state of the art of the MCSRs technology, the different configurations used, the control methodologies, the economic and technical considerations, their selection for specific applications, and the concluding remarks.

2. Working principle of MCSRs

The working principle of MCSR is as if transformer devices work due to magnetic flux phenomenon. MCSR works according to the control of magnetic saturation phenomenon as a magnetic magnifier [74,77,108]. Basically, MCSR consists of iron core with magnetic valves (or stages), AC controlled working windings and DC control windings [108,111]. The basic configuration of the MCSR is demonstrated in Fig. 1. The iron core comprises of two parallel limbs and two yokes [112]. Because of AC and DC windings, AC and DC flux occur in the iron core [73]. Working windings and control windings are installed on two limbs of the core [112]. Magnetic valves (or taps) are on the limbs are deeply saturated when the MCSR works at its nominal current [108].

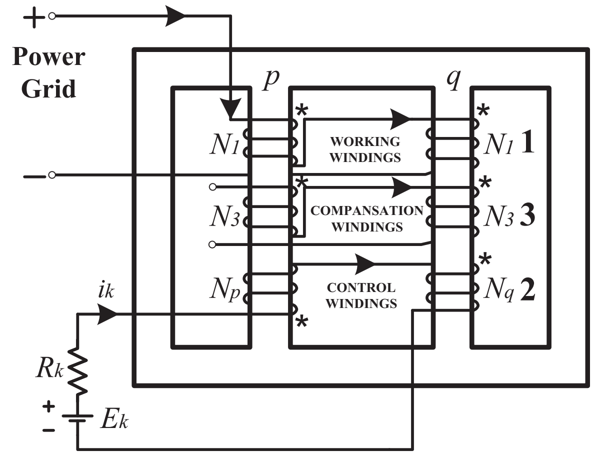

Fig. 1. Core structure and winding arrangement of a single-phase MCSR.

In Table 1, an overview of the proposed protection methods for high-voltage MCSR is presented. These protection methods includes the working winding protection, the control winding protection, the compensation winding protection and the backup protection of MCSR [110].

Fig. 2 shows that the A, X terminals of the working windings are directly connected with the power grid in parallel; Ek+, Ek- terminals of the control windings are reversely connected with DC control voltage in series, and then they are connected with DC control power. Table 2 shows the basic structure of MCSR related with Fig. 2 [92].

In order to obtain the control of the magnetic saturation, not only the winding connection but also the magnetization characteristic is important for MCSRs. The magnetization characteristic of MCSR is defined with the magnetization curve. In [74] the article, the magnetization of the MCSR, DC and AC current control is mentioned. This process seems complicated. However, the basic magnetization curve is selected to simplify the complexity. When the DC control current increases, the working current also increases. And when the control current (excitation) changes, the magnetic saturation level (β) of the iron core also changes. Therefore the magnetic permeability of the core alters and the impedance value of the MCSR is adjusted accurately [108,113].

Table 1
An overview of protection methods for high-voltage MCSR.

Protection zone	Protection function
Working winding	• Separate-side percentage differential • Zero-sequence percentage differential • Zero-sequence directional over current
Control winding	• Over voltage • Negative-sequence directional over current
Compensation winding	• Over current with composite start-up voltage • Unbalance
Backup	• Over current • Zero-sequence over current • Temperature/Thermal

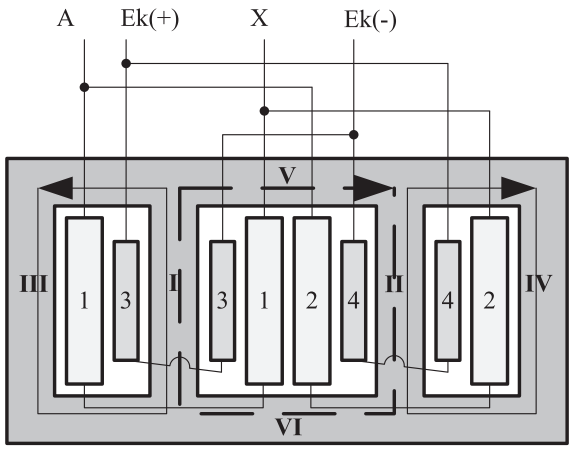

Fig. 2. Cross-section diagram of core and windings (MCSRs).

Table 2
The basic structure of MCSR (Fig. 2) [92,112].

The basic structure of MCSR	
I, II:	Limbs of the core
III, IV:	Return or bypass yokes
V, VI:	Upper and lower yokes
1, 2:	AC controlled working windings
3, 4:	DC control windings

3. Classification of MCSR

3.1. Classification of the power rating and applications

Fig. 3 shows the classification based on the power rating criterion. The power rating of the compensated system plays a major role in deciding the control philosophy to implement the required MCSRs.

3.1.1. Low power application

This type of application is mainly concerned with the systems of power ratings below 100 kVA. It is mainly associated with residential areas, commercial buildings, hospitals and for a wide range of small to medium-sized factory loads and motor-drive systems.

3.1.1.1. Single phase system. The electrical power is generally produced as three-phase AC voltage in power plants and also transmitted as three-phase AC voltage over long-distance transmission lines. Despite single-phase systems are mostly used in residential power systems, some industrial and commercial applications exist as a single-phase [114]. The single-phase low power application of MCSR is an occasional type in literature, as well as the single-phase application is limited in industry and commerce. Nevertheless, the configuration of a single-phase MCSR is frequently used in most MCSR applications owing to the simplicity. Thus, in addition to the diagram that is shown in Section 1, another basic configuration of a single phase MCSR is demonstrated in Fig. 5. Besides, an extra information can be given that the windings on the different limbs are crossly connected and then the two branches of the series coils are connected in parallel to the grid in Fig. 4 [112].

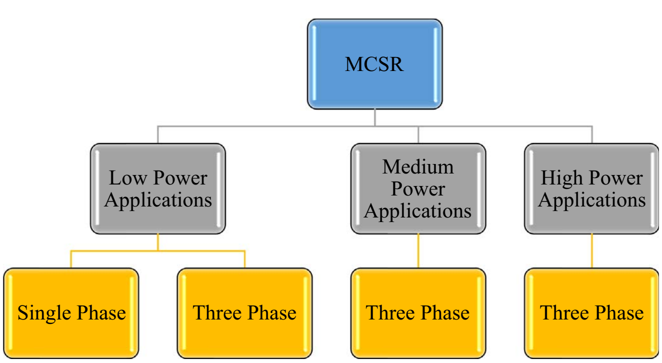

Fig. 3. Classification of power system according to power rating.

By using the configuration in Fig. 4., the design criterion of a MCSR by specifying the crosssection of the iron core, the conductor cross section area and turns of windings was introduced. A prototype of a single phase MCSR, which is based on the proposed design was established [105].

3.1.1.2. Three phase system. Since heavy loads in industries and commercial applications need the AC voltage, three-phase power systems are used in general. Therefore, the three-phase MCSR applications exist mainly against the single-phase MCSRs like all three-phase applications [114]. Some of these three-phase applications are the reactive power compensation and the automatic voltage regulation of the MCSR.

The construction of the three-phase MCSR looks like the three-phase power system in general manner. Therefore, the three-phase MCSR, which is usually used in EHV/UHV systems, consists of the three phase reactor that is given before in Fig. 1. [93]. Thus, the working principle of a single-phase MCSR and a three-phase MCSR is similar. On the other hand, in three-phase MCSRs the connection of the three windings is another issue. The main circuit diagram of a three-phase MCSR is so given in Fig. 5. Three-phase Working Blocks (WBs) on the primary side of the MCSR are connected in "Y" type. Three-phase Control Blocks (CtrBs) on the secondary side are connected in parallel with positive and negative DC buses. In order that both form a loop for zero-sequence harmonics and supply the rectifier via a rectifier transformer, the three-phase tertiary Compensation Blocks (CBs) are connected in "Δ" type. To control the DC current in the CtrB, the firing angle "α" of the rectifier is adjusted and the operating capacity of the MCSR is determined [115].

In the [93] article, the configuration, working principle, mathematical model, electromagnetic model and three operating states of the MCSR are described; the characteristics of the MCR are demonstrated with the numerical simulations. And then a three-phase MCSR with a 2,85 kVAR is verified by the experimental model.

In the [106] article, the application of a three phase MCSR type static var compensator (MSVC) with a 2,2–8,2 kVAR reactive power range is confirmed in Zhaizhen colliery and it is realized that the proposed device has a lot of advantages such as low harmonic and power consumption, easy configuration, low cost, high safety and small footprint. It is also an optimal dynamic reactive power compensator and voltage regulator.

In the [84] article, the specific configuration, operation principle, characteristics and automatic voltage regulation process of the Magnetic Valve Controlled Reactor are presented. The control system is analyzed and a three-phase MCSR simulation model with a 3 kVAR is tested. This study is a low power application for both single-phase and three-phase MCR.

In the [111] article, a structure and a mathematical model of the multi-stage saturable MCR (MSMCR) with no-harmonics are revealed to design a more flexible reactive power control device. The proposed models for both single-phase and three-phase MSMCR are simulated by using with 2 kVA saturable UMEC transformers.

3.1.2. Medium power application

The second type is the medium power applications, which has a

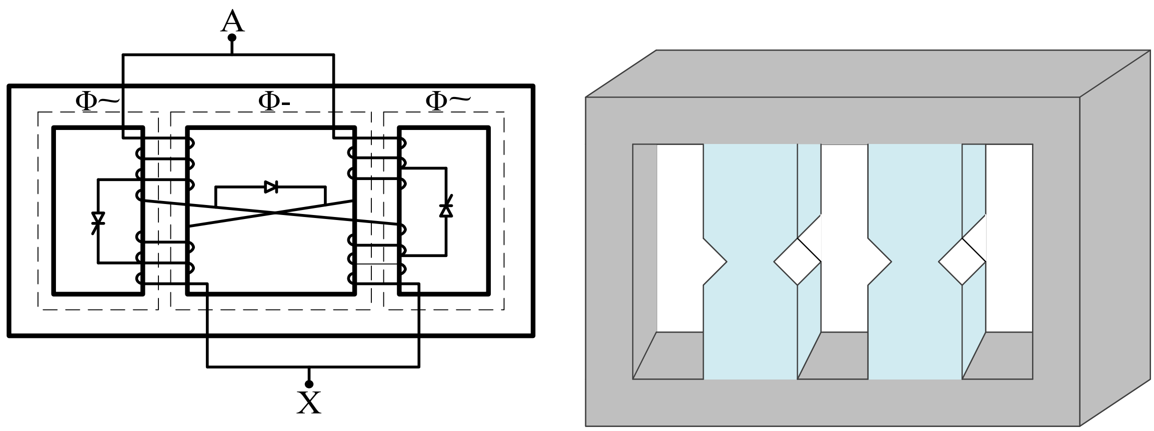

Fig. 4. The basic configuration of a single-phase MCR.

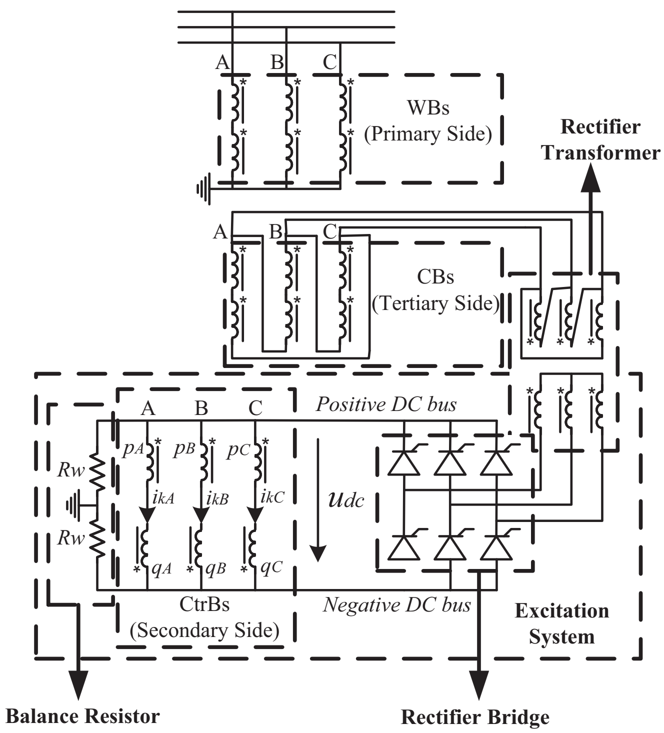

Fig. 5. Main circuit diagram of three phase MCSRs.

power capacity between 100 KVA and 10 MVA. For the medium power MCR applications, reactive power compensation, power quality compensation, soft-starting of an induction motor and the damping of the power system oscillations exist in literature.

In the [116] article aims to solve the multi-objective optimization problem of the robust Magnetically Controlled Reactor with Fixed Capacitor (FC-MCSR) based damping controller design to introduce a novel compensator based on FC-MCSR and then to study power system stability in case of using this compensator by an intelligent control method. The proposed controller is tested in the system, which has a generator with a 8 MVA capacity. The designed Honey Bee Mating Optimization (HBMO)-based FC-MCSR controller by using the proposed multi-objective function has a superior ability while damping the power system low frequency oscillations and significantly enhances the power systems dynamic stability.

In the [107] article, to deal with the power quality problem in a high speed railway power supply system, a new hybrid compensation system based on the railway power conditioner (RPC) and the MSVC with a 6 MVAR capacity is proposed. The hybrid compensation system will decrease the capacity of RPC. The negative current compensation and the harmonic current mitigation are investigated, a control strategy is proposed and the simulation results verify the correctness of the proposed method.

In the [117] article, a novel reduced-voltage soft starting device based on the MCSR is proposed and verified on a 10 kV 5,5 MW system. The experiment results demonstrate that the improved MCSRs soft starter is quite successful, can decrease current effectively and adjust stator current smoothly, fastly and reliably. Therefore, it is much suitable for the starting large medium-voltage induction motor.

In the [97] article, the design criteria for the components of the MCSR and the parameter calculation are presented, the energy efficiency analysis and the risk analysis are discussed. In order to prove the functions of the MCSR, a MCSR application with a 239,7 KVA power in a transformer substation is presented and it is proven that the MCSR is effective, feasible and reliable by the real operating results.

In the [108] article, in order to minimize the response time and solve the problem of the reactive power overcompensation of the MCSR, the novel compensation algorithm which contains parameters of PF is proposed. This algorithm is based on instantaneous reactive power theory and Steinmetz Algorithm, which can compensate the three-phase system to a certain PF value. The simulation results of a 6 MVAR MCSR demonstrate that the proposed algorithm has high precision and good dynamic characteristics.

3.1.3. High power application

High power applications have the power capacity greater than 10 MVA. The MCSRs are almost completely used in EHV/UHV transmission lines. Accordingly, there are lots of MCSR applications at high power rating in the literature [73,76,78,83,85,89–91,98,104,109,115,118–121].

In the [78] article, it aims to design a new method which determines the replacement of fixed reactors with MCSR financially, the most proper location and the capacity of the MCSR for a power system which has a power of 125 MW and 50 MVAR at peak load. The proposed model provides choosing the location more flexibly, determining the fittest capacity for a voltage stability without any economical concern by applying it to a practical study.

In the [118] article, a dual model of the single-winding MCSR is presented in order to simplify the modeling of an electrical network with a MCSR, a 10 kV 10 MVA MCSR is chosen for modeling and it is shown that the proposed model which is based on TCR acts like MCSR.

In the [73] article, the basic concept, the magnetizing behaviors under different DC magnetizing strength and the mathematic model of the orthogonal flux controllable reactor (MCSR+), which is another kind of the magnetic saturation type controllable reactor determined by the direction of fluxes like MCSR. A single phase 50 MVA /550 kV MCSR+ based on the proposed model is simulated and the results demonstrate that the intrinsic second harmonic of the AC currents and DC current, however, the harmonics can be suppressed by using suitable design of the MCSR+. In general, the response time of MCSR+(or MCSR) is quite slow, so a high rated but the short time duty DC power supply is essential to enhance the transient characteristics.

In the [119] article, it is to compare MCSRs and TCRs with regards to the transient characteristics, and a detailed model of a MCSR is used to illustrate the ideas presented throughout the article. A three phase MCSR with 180 MVA 500 kV is simulated. It is shown that a MCSR is better than a TCR, because the operation and maintenance of a the MCSR is as simple as the traditional transformers and they cost twice less than a TCR. The current distortion of a MCSR without any filter is less than a TCR. While TCR requires a highly rated thyristor system, the MCSRs do not require such highly rated thyristors, because the MCSR is based on a low-power magnetic biasing.

In the [104] article, for the high voltage problem at 110 kV side of the power system with 2×120 MVA, coordinated reactive compensation capacity configuration and voltage and var coordinated control method based on the MCSR and MSVC (Magnetic Controlled Static Var Compensator) is proposed. This strategy is a complex control strategy consisting of the MCSR, OLTC, MSVC and CB. The MCSR is used at the MV side for ensure the dynamic continuous regulation of the reactive power.

In the [83] article, the information about structure, the development and application areas of MCSR is given. A three phase 30 MVAR MCSR is used and the characteristics of MCSR have been summarized by comparing frequently used controlled reactors in detailed. And, it is concluded that the optimization of the structure of MCSR should be done in order to reduce the loss, the advanced control strategy should be used to enhance the response speed of MCSR and the design of MCSR should be done comprehensibly by minimizing noise and harmonic of MCSR.

In the [76] article, a three phase MCSR and a three phase TCR are compared with regard to their harmonics and a 180 MVA MCSR is modeled. It appears that MCSR has remarkable advantages over TCR and MCSRs are preferable refer to TCRs. MCSR is used in Russia, China and Brazil.

In the [85] article, an AC long distance transmission system with 180 MVA MCSR is proposed as a reliable interconnection between the distant transmission systems. For system stability, a mixed installation consisting of a conventional reactor (SR) and magnetically controlled shunt reactor (CSR) is proposed. It is provided that the satisfactory properties show in damping low frequency inter-area oscillations, when appropriate control systems are used.

In the [120] article, an adaptive tracking algorithm for dynamic time-varying control based on the extensional model and linear regression algorithm of EHV and UHV MCSR is proposed. The proposed algorithm is simulated for a 100 MVA system.

In the [115] article, it aims to find the reason of the undetected overvoltage protection problem when a turn-to-turn fault occurs in the control winding of MCSR, which the conventional protections may run in an unapproved time delay or insufficient in some fault conditions. A MCSR with 3×110 MVAR capacity is used in the simulation. The reason of this problem is demonstrated as the zero-cross of the total control current on which the appearance of overvoltage on dc buses is dependent and so, the fault is undetected when the total control current is unable to cross zero. Furthermore, a new protective scheme, which can detect 2% of the fault by installing only one electrical or optical current transformer on the dc bus, is proposed.

In the [89] article, to develop a compound flexible control strategy of magnetically controlled shunt reactor in load shedding case is aimed. The proposed control strategy is simulated with a 600 MVA system. It enables that suppress the frequency over-voltage of capacitive voltage rise in load shedding, decreases the system impulse, over-voltage time and enhance the voltage control accuracy.

In the [90] article, an overvoltage problem on the dc bus of the MCSR and a harmonic problem on the grid occur, when a MCSR is energized directly, a new energization method with the dc pre-excitation in the control winding of MCSR is improved. 3×60 MVAR MCSR is used in the simulation. As a result, the pre-excited energization for a MCSR is possible. The control current carries both the dc component and the harmonics under a steady-state operation. The energization with a dc pre-excitation in the control winding can mitigate the overvoltage on the dc bus and the harmonics caused by the direct energization. In order to estimate the dc current value with suppressed the transients for a well-done energization, the numerical simulations are sufficient. In the [90] article, it is suggested that the certain dc current be evaluated by the field tests for each MCSR. High order harmonic currents in the control current because of the pre-excited energization should be considered and when the thyristors of the rectifier are selected which can withstand overcurrent, the special aspects should consider.

In the [91] article, it is to analyze the dynamic harmonic characteristics caused by MCSR. A simulation is applied to the 100 MVA power system. Unlike the conventional harmonic sources, during the over-voltage dynamic control of MCSR, there are both odd and even harmonics exist; the amplitudes of odd and even harmonics are similar in magnitude, and decreasing in sequence in the transient process. During the transient process, the distribution of each harmonic is balanced and the amplitudes of harmonics rise in more than 10 times frequency.

In the [98] article, it shows the application of the adjustable sources of the reactive power(SRP) based on a 25 MVA MCSRs and capacitor banks in 110–500 kV grids and its advantages. By using an example, the efficiency of a controllable reactive power compensation is demonstrated. The prevalent applications of MCSR and the capacitor banks-based SRP in the power lines at 110–500 kV voltage level will allow to substantially minimize the damage from the power supply interruptions and to decrease the need for a new power transmission line construction thanks to the most efficient use of efficiency of the available lines. Total power of SRP in a network may be at least 100% of the maximum consumption of the power for 110–500 kV grids.

In the [121] article, it investigates the harmonic characteristics of the current, voltage and magnetic field of the MCSR with a 60 MVA. The reactor's; working current is an odd harmonic function, containing the fundamental wave and the odd harmonic components; controlled the current and the voltage are even harmonic functions, containing DC and even harmonic components; the core flux linkage, flux, magnetic field intensity and magnetic field density are just containing DC and the fundamental components are seen.

In the [109] article, to analyze the principles and characteristics of the MCSR and present a continuously adjustable reactive power compensation device based on the MCSR for substation, using its capacity to adjustment smoothly is aimed. The used control strategy is easy, with the quick response speed and low harmonic. By improving and applying the control strategy in a power system with a 120 MVA capacity, the results of the simulation work and the field application were analyzed. It is proven that the device satisfy the design requirements by the simulation and application results. The MCSR can track and answer to the system voltage and the reactive power demand rapidly to solve the problem that the high side voltage and the voltage fluctuation of a medium side are very high and it can supply a large reactive power and voltage support in various operating conditions.

3.2. Classification according to the power circuit configuration and connections

The magnetic valve or stage concept is mentioned in Section-I. At first, MCSR is designed as a single stage device. The current harmonic

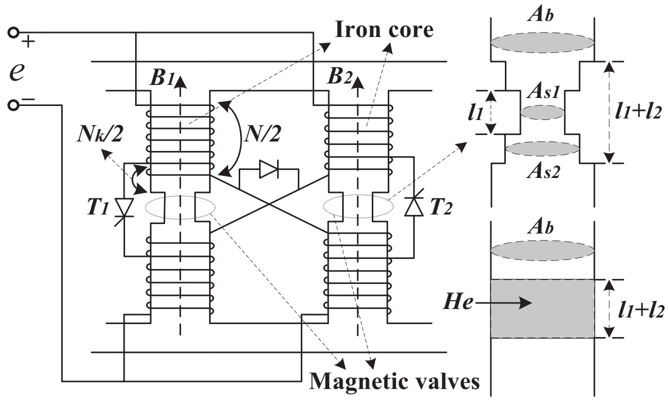

Fig. 6. Design of the stages in the iron cores of a two-stage MCSR.

characteristics of a single-stage MCSR are presented in [109] article. However, in order to reduce the harmonics of the MCSR, the multi-stage core structure is shown up [111]. The design of the magnetic stages of a two-stage MCSR is demonstrated in Fig. 6 [75].

In the [111] article, the harmonics analysis of a multi-stage saturable MCSR (MSMCSR) is proposed with the core structure and the mathematical model. The core is modeled as more than four stages. In multi-stage MCSR, the harmonics produced by the stages can be compensated for each other automatically, because the stages are saturated at different times. So, the total harmonics of the MSMCSR go down below the conventional MCSRs. The simulation verifies the theoretical results of the proposed model and it shows that the current harmonics in the single phase MSMCSR are strongly decreased.

In the [75] article, the structure and the mathematical model of a two-stage saturable single-phase MCSR (TSMCSR) as arc suppression coils are presented. This research introduces two important parameters as k (the area ratio of the second stage to the first stage) and m (the ratio of the length of the first stage to the total length of the magnetic valve in the iron core) that influence the harmonic current of the TSMCSR. An optimization algorithm is also offered to search for the ideal value of k and m.

In the [100] article, a novel Continuously Adjustable MCSR (CAMCSR) is offered to prevent the control "blind area" and reduce the output harmonics of the traditional MCSR as in Fig. 4. The CAMCSR has circular truncated cones in the iron core and the harmonics in each section of the core are phase shifted each other and the total harmonics are decreased strongly against to the traditional MCSR. The CAMCSR can be considered as a multi-stage MCSR. The flux density distribution of the CAMCSR is more regular than the traditional MCSR and the edge effect, the magnetic flux leakage divergent, the additional stray and the copper losses of the traditional MCSR is decreased.

In the [102] article, the power loss analysis of the core and coil for both a single-stage and a multi-stage MCSR are analyzed. The simulation results demonstrate that the magnetic field distribution is uniform; the prevention of the edge effect is clear and the power loss is smallest. The core loss was 47.6% lower, and the coil eddy current loss is 62.9% lower than that of the single-stage MCSR.

3.3. Classification according to compensated variables

The MCSR is used for different types of applications. For example the overvoltage suppression, the restraining voltage flicker, the reactive power compensation etc. are one of these applications. The classification according to the compensated variables is shown in Fig. 7.

3.3.1. Reactive power compensation

In the power system, the fluctuation of the reactive power balance causes to a distortion effect. While the oscillation in the system voltage is occurred, the energy efficiency is reduced because of the distortion effect. Thus, the reactive power balance is so important between the source and the load side [134–137]. For this purpose, the reactive power compensation is achieved at the source side of the system.

The MCSRs are operated with the capacitor group for the reactive power compensation. The MCSR and capacitor group are parallel connected to each other. These capacitors increase the system voltage by producing to the reactive power while the power system voltage increases. When this increase exceed the upper limit of system operation, the overvoltage phenomenon occurs. The long term overvoltage leads to system fail. The MCSR can used to counteract overvoltage which arising from the capacitive effect of transmission lines, especially long distance transmission lines. In the [97] article, the MCSR acts like an inductive user and uses the reactive power. In this way, the voltage of the power system decreases.

For the reactive power compensation, the response speed of the MCSR is an important issue. To increase the response speed of the MCSR, using a control circuit based of IGBT [103] and rectifier circuit based on the PWM converter [96] are fast compensation studies in literature.

At the same time, avoid to over the compensation of the MCSR is another aspect. In the [108] article, using an algorithm based on the instantaneous reactive power theory and Steinmetz algorithm, response time of the MCSR is reduced and the three phase unbalanced loads are compensated effectively. The MCSR compensates the reactive power and improves the power factor in substations by using conventional topology [107,129].

In substation, the MCSR can used with its conventional topology to improve the power factor and the compensation with constant value. In this situation, the power factor is 0,8 without the MCSR. But when the MCSR is implemented to the system, the power factor improves about 25%. In the [97] article, the constant value compensation is changing to output the capacity of the MCSR according to the variable reactive power of the system for a constant power factor value.

3.3.2. Harmonic compensation

The harmonic is a sinusoidal waveform that is the different from the system basic sinusoidal waveform. Harmonics causes nonsinusoidal waveform of the voltage and the current with distorting. Thus, the increasement loss and resonance are occurred in the system caused by the harmonics. For this reason, the harmonic compensation becomes more important issue for the power quality improvement [134–137].

In the [122] article, to reduce the harmonics to the system, a magnetic valve structure is added to the DC control windings of the MCSR. In this way, only magnetic valves are saturated and the flux density is controlled. Thus, the core is saturated with the harmonic controlled.

In the [85] article, using the conventional reactors and controlled reactors combination the harmonic control is ensured for 500 kV long distance transmission lines,. In this method, the line current, CSR terminal voltage and frequency deviation are controlled. Thus, the steady-state and the transient-state stability are provided.

In the [123] article, the secondary control windings and the capacitor on DC side of the voltage source inverter are connected using BUCK circuit for the DCCR type of the MCSR. In this way, harmonics are eliminated using the active power filter based on a voltage source inverter.

3.3.3. Compensation of voltage harmonics

Voltage harmonics arise from distortionary effects on voltage waveform by the current harmonic. The voltage harmonics cause the instability of the system voltage and the flicker phenomenon. In the [84] article, the compensation of the voltage harmonics means voltage regulation. The MCSR regulates the voltage effectively.

For the suppress overvoltage, a control strategy which include coordinated breaker is selected in literature. In this strategy, the MCSR

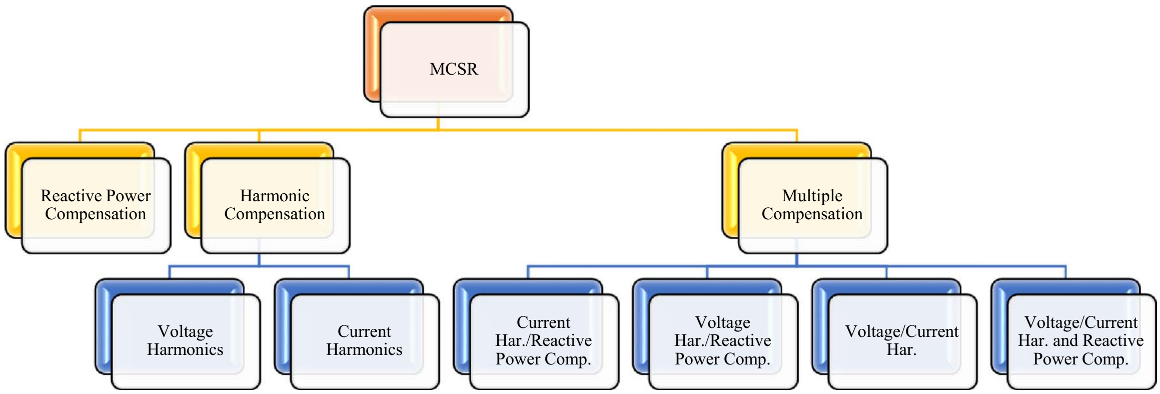

Fig. 7. Classification according to compensated variables.

and the breaker are operated same time. In the [89] article, the overvoltage and the voltage flicker are suppressed by using this strategy. When the magnetic saturation degree increases, the capacity of the MCSR also increases. In the [81] article, the changing of impedance of the MCSR provides to change of the line voltage.

The magnetic saturation degree is changed by the DC excitation. Thus, the output capacity of the MCSR changes and the overvoltage of the system is suppressed in the [120] article.

In the [98] article, to minimize the damages caused of the voltage interrupt, using SRP based on the MCSR and CB is proposed in 110–500 kV transmission system. Thus, the voltage stability is obtained fast in the proposed system.

The Capacity of the MCSR depends on working the windings current. This current is obtained through regulated the DC voltage. In the [124] article, using ideal power supply, the high harmonic of the power system and the harmonic components of the DC voltage are eliminated after rectified.

The transient stability of the power system is improved by the MCSR. This result is observed at the transient analysis of long distance transmission lines. For the improvement, the CSR terminal voltage mode is used at some critical situations. The CSR terminal voltage is adjusted by the variable reactive power in the [85] article.

In the [91] article, the dynamic overvoltage suppression capability of the MCSR is analyzed using the electromagnetic transient modular of the ADPSS. According to analysis, in transient situation amplitudes of even and odd harmonics are duplicated. However, the control of the current harmonic is ensured the control of the voltage harmonic indirectly.

3.3.4. Compensation of current harmonics

The current harmonic is distortion of the waveform of the system current component. Lots of power system components such as non-linear loads and induction machine are caused current harmonics. The current harmonic causes the power loss, the fault of sensitive device and secondary aliasing as voltage harmonic. Also, the current harmonics make difficult of system operating.

In the [125] article, at the single phase-ground faulty conditions, EHPC (Electromagnetic Hybrid Petersen Coil) based protection method is used for protection. EHPC includes APC (Active Power Compensator) and MCSR. This protection method is called flexible neutral grounding method. According to this method, in normal conditions, the system is grounded by the way of reactor which has high resistance. When the single phase- ground phenomenon occurs, the EHPC suppress the recovery voltage of the failure phase and the ground faulty current is reduced above zero. For the harmonic components of ground faulty current, balancing and displacement the voltage at neutral point method is adopted in this method.

In the [101] article, the current harmonics are observed under the variable AC working conditions. In this situation, the harmonic suppression windings are added to the DC control windings for eliminate to harmonics.

In the [117] article, an induction motor can be started by a constant current. To obtain the constant current, the MCSR is usable. For this purpose, thyristors are triggered by the controller to produce six pulse signal. Thus, controlled DC current is produced for magnetic valve saturation. The MCSR output current capacity is adjusted by the trigger angle. Finally, the crank of the motor is made smoothly.

In the [90] article, using pre-excitation system, distortion of the transient inrush current on primary side of the MCSR is reduced. In this way, while the current harmonic is reduced, the overvoltage on the DC bus is suppressed.

In the [115] article, a control strategy based on the total control current of the control windings is used for a overvoltage protection for turn-to-turn fault conditions. According to the strategy, ETC or OTC is selected for eliminate to the DC components of the control current. For operate properly of relay, the over current relay should be set the levels of unbalance seen in a normal service either due to system unbalance or due to the manufacturing tolerance of the MCSR.

In the [93] article, for the eliminations of the harmonics such as third harmonic which from a flow path for zero sequence harmonics, secondary control windings are delta connected.

3.3.5. Multiple compensation

The aim of multiple compensation is compensate to the more than one system factor such as a harmonic and a reactive power at the same time. Although these systems have a complex structure, more effective and extensive compensation is ensured.

The reactive power control can be made easier by optimizing the harmonics. In the [111] article, the multi-stage saturable MCSR due to its structure is reduced the output harmonics. Toimprove the harmonic performance, Particle Swarm Optimization is used. Thus, the reactive power control capability of the MCSR is occurred.

In the [109] article, the real-time monitoring of the system voltage, current and power using several algorithms, an effective voltage regulation and a reactive power control are achieved for SVC based substation.

In the [92] article, using the look-up table method, the switching overvoltage and switching transient overvoltage is limited. The transmission of the inverse reactive power is disposed.

In the [104] article, the MCSR is connected to MV and LV voltage levels. The MCSR ensures to the voltage stability at MV. At LV level, both MCSR and CB compensate to reactive power together for MSVC based multi side coordinated reactive compensation system in substation.

In the [76] article, the MCSRs are more effective than TCR in many application areas with regard to the automatic voltage regulation, reduced the fluction and smoothing of the reactive power surges.

In the [106], the usage of the MCSR gives satisfactory results for a reactive power compensation, a power factor improvement and a voltage regulation at coal mine applications.

In the [76] article, changing the magnetic permeability of the core, the MCSR output voltage and the reactive power capacity are adjusted. In this way, the reactive power compensation and voltage regulation of the system is ensured.

In the [126] article, the dual excitation system ensures the high speed excitation and the short response time for the MCSR. The MSCR with realized advantage becomes the ideal solution for a required high speed compensation like a wind electricity reactive compensation. However, with the resistor depend on voltage which is called MOV, the excitation circuit protection is ensured against to overvoltage.

In the [81] article, the performance of MCSR is investigated on UHV transmission lines. The transient and steady-state simulation is realized for this aim. According to results, the MCSR is very effective for a stability on transient and steady state conditions.

In the [119] article, the transient behaviors of the MCSR and TCR are simulated on MATLAB platform. According to results, the MCSR and TCR show similar behaviors about the reactive power change ratio. When load increases, firstly MCSR has time delay per TCR, but then, reactive power rate of the rise of the MCSR and TCR are the same. The TCR response time is short than the MCSR's. But this situation of the MCSR is negligible because the power system voltage is not a salutatory phenomenon.

In the [85] article, the capacitive effect of the transmission system causes a voltage rise. Especially, during the minimal load, this negative effect is more significant. In transmission systems, for ensure to transient and steady-state stability, the MCSR has three control modes which are called line current, the CSR terminal voltage and the terminal frequency deviation modes [85].

3.4. Classification based on the control technique

The capacity of the MCSR is controlled by the DC control current that is obtained from the DC control windings of the MCSR. The DC control current is adjusted by changing a thyristor trigger angle. The saturation degree of magnetic circuit of MCSR changes with change of DC control current. In this way, impedance of the reactor changes and the MCSR capacity is adjusted. The classification according to the control techniques is shown in Fig. 8.

3.4.1. Open Loop Controller

The open loop control has not feedback. That means, the control system is not sensitive to aliasing. Thus, this control method is preferred for the system that is nonsensitive and well known with the structure and variables. This method is not preferred for a multivariate system as power network.

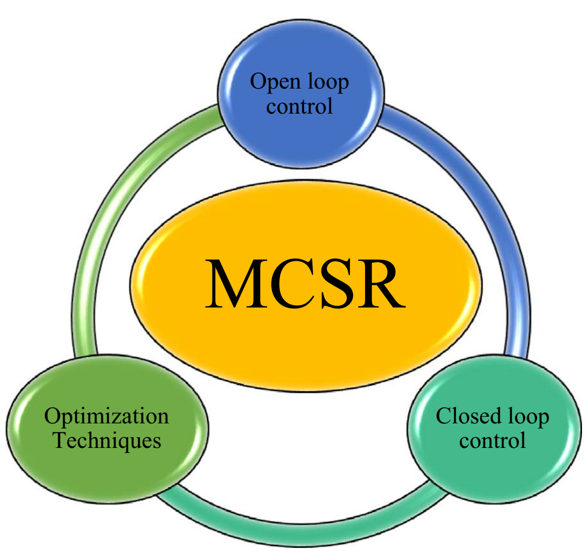

Fig. 8. Classification according to control techniques.

In the [125] article, the EHPC which includes the MCSR and the APC based neutral grounding method is used for distribution systems,. In this method, two stages compensation is mentioned. First step is the open loop compensation. When a fault occurs, the EHPC compensates using the open loop according to prescribed parameters. In this way, the faulty feeder output is identified.

3.4.2. Closed Loop Control

The closed loop control system is also known feedback the control system. In this control, the disturbing effects are considered by a control mechanism. Thus, the real time and high sensitive control is ensured.

The second step of the EHPC based neutral grounding method is the closed loop compensation. After identify the faulty feeder output by the open loop compensation, the EHPC proceed to the next step which is the closed loop compensation. In the [125] article, displacement voltage of the neutral point and the neutral-ground impedance are controlled in this stage.

The closed loop control is used frequently at the MCSR control. In the [84] article, the closed loop controlling model includes measuring the loop, comparing loop, filter, PID loop, the synchronous, signal circuit, moving phase circuit and driving circuit.

In the [123] article, the closed loop applications use the conventional PI controller for an inductor control. Furthermore, in the [127], the control system is consist of PID controller and DC-DC converter based on IGBT on the side-limb winding for the SSMCSR which is a kind of the MCSR. PID controller has the closed loop structure that uses a phase angle for feedback.

In the [117] article, the current control strategy is used the soft starter that is a kind of the closed loop control. The feedback signal is achieved from a motor current. The thyristor trigger proceeds until the motor current drop to below 1,1 times of a nominal current.

In the [76] article, the control of the MCSR is ensured by the variable permeability of core. The change of trigger angle, control winding voltage of the MCSR is changed. The MCSR can use the same control structure with TCR. In such a case, the saturation degree is used for the feedback of the closed loop. In this way, the output voltage and the reactive power are adjusted.

In the [128] article, the closed loop control is used for the algorithm which is used for an electromotor soft starter. In this control, the reference current and the controlled current are compared. If the controlled current is bigger than the reference current, trigger angle and impedance of MCSR decreases. If the controlled current is smaller than the reference current, trigger angle and impedance of the MCSR increases. MCSR controlled by FPGA and PLC. The first trigger angle is supplied through PLC. Other five trigger angle is supplied through the FPGA after time delay 60°. The MCSR is driven with the six pulse trigger signal.

3.4.3. Optimization techniques

An optimization means manage to process with minimum loss and maximum yield. As in many areas, the optimization techniques are used for an efficiency in power systems. The optimization techniques in the literature can be listed in Fig. 9.

In the [111] article, the PSO algorithm can be used. this algorithm is modified for minimizing to the current harmonic For the improvement harmonic performance of the multi-stage saturable magnetic controlled reactor.

For the effectiveness of the MCSR, the location of the installation is very important. In the [78] article, the evaluation algorithm (EA) finds the set of optimal Pareto solutions that decision maker's decides the best optimal solution based on the different aspects. The best Pareto solution is the output of the invasive weed optimization (IWO) which is

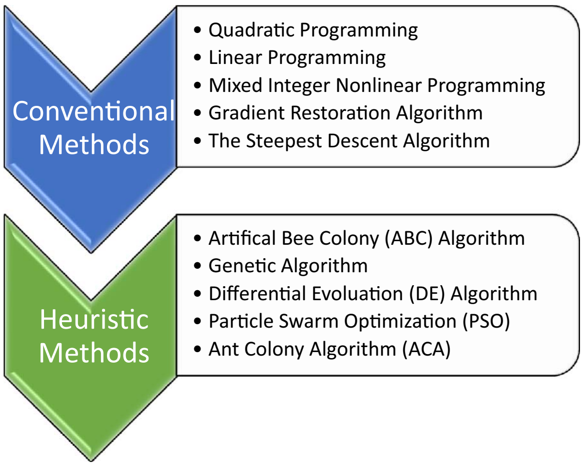

Fig. 9. Classification of Optimization Techniques.

a kind of EA. The chosen solution depends on decision maker's expectation totally. All objectives are compared numerically on AHP. The AHP gives objective. The sorting of the solution is identify by TOPSIS method. The output of TOPSIS is best answer of the capacity and location. The optimization studies based on the new improved or changed control algorithms are in the literature.

In the [116] article, the FCMCSR based on a novel compensator is designed. Some optimization problems come up against at the design stage sustainably FC-MCSR based on a suppressing controller. For the solution of this problem Honey Bee Mating Optimization (HBMA) Algorithm is used. The designed HBMO based FC-MCSR controller by using the proposed multi-objective function has a superior ability while damping the power system low frequency oscillations and significantly enhances the power systems dynamic stability.

In the [127] article, a control system based on IGBT which includes DC-DC converter and PID controller is used for the control of SSMCSR. PID Self Tuning Algorithm is used to closed loop control. In this way, the response time of SSMCSR is improved and smoothly control is ensured. Over oscillation is above zero using this algorithm.

In the [108] article, using an algorithm based on Instantaneous Reactive Power Theorem and Steinmetz Algorithm, the response time of MCSR is reduced and the overcompensation is prevented. For the improvement algorithm, the linear voltage positive sequence is converted to two phase static coordinate system using the clark transform. The load current positive sequence is converted to the DC components and the load current negative sequence is converted to the AC components using the Clark and Park transform, respectively.

In the [120] article, an adaptive tracking algorithm is developed for the dynamic time-varying control of EHV and the UHV applications of the MCSR. The aims of the control are reduced transmission loss, suppress the overvoltage, ensure fast a response and low harmonic. The dynamic identification algorithm is used for the control system. For the phase measurement method, the benefits from Fourier transform. Finally, the least squares theorem is chosen for a parameter tracking formula. The simulation is realized the electromagnetic transient modular of PSASP. The voltage is adjusted in examples, the instantaneous voltage waveforms are recorded in a stable and transient state, the error comparison is made to confirm the validity of the proposed model.

In addition to the optimization manners based on the control system, the MCSR performance is improved changing the MCSR structure and the excitation system. The study of the optimizations in the MCSR topologies excitation system is in the literature.

In the [101] article, the MCSR topology is modifiable for produced harmonic under a different AC working condition. The harmonic suppress winding is added to the control side. In this way, the response time and harmonic oscillation are reduced.

In the [103] article, the control circuit of the MCSR can modified. For this aim, the control circuit of the MCSR is designed based on IGBT to obtain for the fast response time,. Thus, the fast response and quick demagnetization is obtained.

In the [93] article, the primary windings are Y connected because of the secondary current compensation through the single phase fault reclosing. The secondary control windings are Δ connected for the harmonic elimination because of the flow path of the zero sequence harmonics. The DC control current which regulates the capacity of the MCSR controls the saturation degree of the iron core. Using a control strategy based on this basis, the MCSR capacity is adjusted.

In the [123] article, the harmonics of DCCR type MCSR is eliminated using the harmonic compensation winding. The harmonic compensation winding is added to every primary winding. Using a BUCK circuit, the secondary control winding and the capacitor of DC side of the voltage source inverter are connected. However, the control method benefit from the instantaneous reactive power theorem.

In the [90] article, the pre-excited system can usable in the MCSR for preventing to over voltage and harmonics.

If using a new excitation topology which has a simple control circuit and a simple trigger circuit, a high speed excitation and a short response time are obtained in the [126] article.

In the [96] article, using the voltage type PWM converter, the fast response is ensured for the MCSR. In this structure, a PWM which operates two modes are an inverter and a rectifier, is added to the control circuit. The fast response is obtained by the DC control strategy which is used for PWM. However, the various control strategies are developed for the MCSR control.

In the [89] article, using the compound flexible control strategy, overvoltage is suppressed. According to this strategy, the first step is breaker operates, then the control signal is sent to the MCSR. The MCSR and the breaker operate at the same time for the overvoltage suppressing.

In the [92] article, a control strategy based on the reactive power and the voltage control can use for the dynamic reactive power compensation. This strategy has three control modes which are voltage sub-time, an inverse voltage and a specific control. In this strategy, the look-up table method and the PI controller is used for the control of the MCSR.

In the [117] article, a current control strategy is proposed for the induction motor soft starter based on the MCSR. According to this strategy, the controller generates six pulse signals to trigger the thyristors. The capacity of reactor is adjusted with the control of the thyristor conducting angle.

3.5. *Classification according to current / voltage reference-estimation technique*

The reference current/voltage to be processed by the control loops constitutes an important and the crucial measure for subdividing active-filtering techniques. Fig. 10 illustrates these estimation techni-

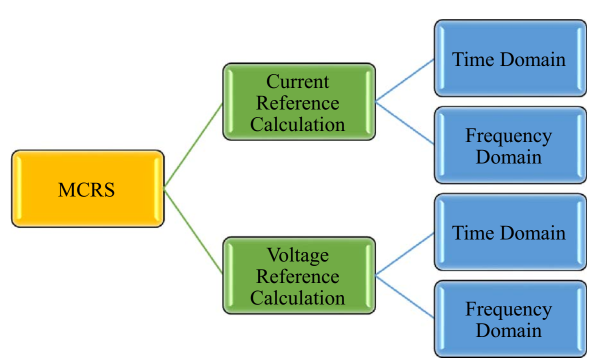

Fig. 10. Classification According to Current/voltage Reference-Estimation Technique.

ques, which cannot be considered to belong to the control loop since they perform an independent task by providing it with the required reference for a further processing. Despite the fact that some references do not mention their source of the compensating-current reference, these estimation techniques can be classified as follows.

3.5.1. Continuous Time-Domain Control

In the [102] article, the optimization of structure of the MCSR's magnetic valve is done using Ansoft Maxwell Simulation Software. The power loses of the single-stage and the multi-stage MCSRs are investigated at time domain.

In the [91] article, the dynamic harmonic characteristic of UHV/EHV MCSR which has combined the AC and the DC excitation system are analyzed. A calculated algorithm is developed using the Fourier series and rectangular theorem. The harmonic analysis is realized on time domain.

In the [108] article, a new control algorithm is developed for solving the overcompensation problem and reducing the response time of the MCSR. This algorithm is improved using the instantaneous reactive power theorem and Steinmetz Algorithm. The park and clark transforms are used in this algorithm. The instantaneous reactive power theorem based algorithm can calculate the parameters quickly.

In the [104] article, MSVC based on the multi side coordinated reactive compensation system which is used in substation, for the control of voltage at MV and LV side, time-share inverse control method is used. This method adopts to a different voltage control range to load a current peak and the valley periods of substation. Furthermore, in the [90] article, the DC bus voltage of the MCSR with pre-excited and without pre-excited are analyzed at time domain. In the [123] article, the total compensation method of DCCR based on the instantaneous reactive power theorem.

In the [73] article, the current of the orthogonal flux controlled reactor which used transmission lines are investigated at time domain. The distortion of the output current waveform of the MCSR which shown in analysis results causes a low load condition.

In the [116] article, the HBMO based on FC-MCSR is simulated at the nonlinear time domain. When a six cycle three phase fault phenomenon occurs, the transient stability is researched. According to obtained the results, the effectiveness of the proposed control method is shown about suppress the low frequency oscillations.

3.5.2. Discrete-Time or Frequency Domain Control

The current harmonic of TSMCSR can analyzed using MATLAB. In the [75] article, the FFT is used for the analysis of the output current of the TSMCSR which rises theoretically.

In the [116] article, to hold down to the harmonic current components of HBMO based on FC-MCSR, Fourier analysis is realized. The controllable susceptance of the fundamental harmonic is controlled by the angle which is generated by the DC voltage and used in the Fourier analysis.

In the [122] article, the numerical method is used. Using the nonlinear Magnetic Field Analysis based on the Magnetostatic Finite Element Method harmonic generation profiles of the MCSR and the VMCSR is obtained for an effort to analysis of the harmonic suppression of the MCSRs. The DFT is used to obtained the harmonic components of the AC windings.

In the [109] article, the FFT algorithm is used to identified to the voltage, current and power of the power system, for the MSVC based on a multi side coordinated reactive compensation system which is used in substation.

In the [91] article, the dynamic harmonic characteristic of the UHV/EHV MCSR which has combined the AC and the DC excitation system are analyzed. A calculated algorithm is developed using the Fourier series and the rectangular theorem. The harmonic analysis is realized on the frequency domain.

In the [107] and [129] articles, the MCSR which is used in hybrid system is controlled the PI controller. The rms value of fundamental current component of the MCSR is calculated using the FFT.

In the [120] article, In the developed adaptive tracking algorithm for the MCSR control, the sliding window algorithm of the DFT is used for the phase measurement method.

In the [123] article, the control scheme of the DFT, the power balance concept gets across. The calculation of the reactive power balance benefit from the Fourier Algorithm.

In the [86] article, the irregular behavior of the MVCSR which cause turn ratio is analyzed using the bifurcation theory. For analysis, the discrete mapping model of the MVCSR is obtained. For this model the fixed period discrete mapping modeling method is used. The simplified integral formula of mapping is obtained using the Taylor Formula.

3.6. Selection considerations of MCSR for specific applications

The magnetic controlled reactor is used for the transmission systems usually. Using the MCSR in the transmission systems reactive power is compensated, the over voltage and the oscillation of the power system are suppressed, transmission capacity is increased and power factor is improved etc. The MCSR can usable to a different application for a similar objective.

In the [125] article, the EPHC based neutral grounding method is used for the distribution system. The EHPC includes the APC and the MCSR. Neutral point of the system grounded by way of the MCSR. When a single phase-ground fault phenomenon occurs, an open loop compensation starts. The open loop compensation needs to preset a value. The inductance of the MCSR is adjusted to preset the value which is identify for the open loop compensation. In the open loop step, the faulty phase is identified. The next step is the closed loop compensation. When the tangent of angle which is between the phase voltage of the power supply and the displacement voltage reduces to 0,15, the MCSR move to the closed loop phase. When the tangent of an angle nears to zero, the APC begins to start. In this way, the power frequency component of the fault current is almost wholly suppressed. The time of arc suppress is decreased.

In the [104] article, the different devices are combined for a complex compensation system. For example, in main substation, the voltage and the reactive power are coordinate compensated. The HV bus, MV bus and LV bus are controlled respectively. The MCSR which is used in the system is connected to 110 kV bus. The MCSR compensates to 110 kV very effective. However, it contributes to the voltage control at 10 kV bus.

Electrical vehicles used for mining area. These vehicles are so effective to the distortion of the system stability. Thus, the compensation is important for this area. In the [106] article, a MSVC application is realized in Zhaizhen Coal Mine. The missions of MSVC in this application are compensated the reactive power, reduced the harmonic value, suppressed the voltage oscillation and improved the power factor. The MSVC includes a wave filter for a harmonic damping, the MCSR and fixed capacitor bank for the reactive power compensation. The MCSR branch includes the MCSR, the thyristor valve tank and the automatic controller. The MCSR ensures an effective compensation due to an automatic compensation. The reason for the preference of the MCSR is a low harmonic value than TCR, although the MCSR has the long response time than TCR.

In the [107] and [129] articles, the hybrid control strategy is used for a negative sequence current compensate and a harmonic current suppress in high speed railway applications. This “Electromagnetic Hybrid Power Quality Compensation Strategy” includes a series of compensation devices. This system consists of the RPC and the MSVC. The RPC can make a effective compensation to the negative current, the harmonic current and the reactive power. In the hybrid system, RPC is used for an active power transfer and a high order harmonic suppression. The MSVC includes the MCSR and harmonic filters. These filters are passive filters and used for 3rd and 5th harmonics. In the hybrid

Table 3
An overview of MCSR articles in literature.

An Overview of MCSR			
Topology	Single-phase	75, 92, 93, 99, 100, 105, 110, 113, 117, 118, 122, 123, 124	
	Three-phase	76, 84, 90, 91, 108, 109,110, 115,124, 125, 127, 128, 130	
	Single-stage	99, 102, 109	
	Multi-stage	75, 100, 102, 111	
Controller	Over voltage	81, 84, 90, 96, 115, 120, 131	
	Current	81, 93, 96, 101, 102, 103, 117,126, 131	
	Impedance	101, 104, 125	
	Harmonic	Frequency-domain	75, 109, 131
		Time-domain	73, 90, 91, 100, 116, 122, 125
		Transient analysis	91, 119
		Steady-state analysis	121, 130
	Reactive power	81, 92,96, 97, 103, 104, 106,107, 109,123, 126, 108	
	Optimization	78, 111, 75, 79, 100, 108, 109, 128	
	DC voltage	92, 96, 102, 109, 124, 126, 131	
Simulation	MATLAB/ SIMULINK	75, 76, 79, 90, 100, 102,104, 107, 108, 115, 119, 123,127	
	PSCAD/EMTDC	111, 113	
Experimental		81, 84, 93, 101, 103, 105,113, 117, 124, 127, 128	
Application		75,78, 85, 91,95, 98,106, 109, 113,115,116,117, 122,124, 125, 126, 128	

system, the missions of the MSVC are compensate to a reactive power and support to the RPC for the harmonic suppression. In the fundamental domain filters are capacitive, and the MCSR is a changeable reactor. Thus, the MCSR and filters are used together. In the harmonic domain, the MCSR is modeled like a harmonic current source. For the developed control strategy, the instantaneous phase detection method is used to reference signal. For the MCSR control, the PI regulator used. The FFT used for actual measured of the MCSR fundamental current RMS value. With the hybrid compensation system, the THD is reduced from 18,08% to 0,98%. Three phase unbalanced current is dominated. With the harmonic suppression, the feeder arm current waveform is likened to a sine waveform. For this application, a prototype is developed. The prototype has a low capacity laboratory-scaled hardware structure. The obtained results from the experimental study are close to the simulation results and the error which between the simulation and experiment is acceptable level in the [129].

In the [117] article, a soft starter is used for limit to the inrush current of an electrical motor. The MCSR based on the soft starter ensures to reduced the inrush current and lower to harmonic level. The MCSR is parallel connected to stator windings. MCSR acts like an adjustable resistance for the limit starting current. When the stator current drops below to 1,1 times of nominal current, The MCSR is short circuit. In this way, the soft starting is obtained for motor. This soft starter is applied to the motor which voltage level is 10 kV and the power value is 5500 kW in Changping Group (Shanxi Province). The effectiveness of MCSR based soft starter is proved at field tests.

Table 3 summarizes the overview of MCSR articles in the literature.

4. Conclusion

An extensive review of MCSRs has been presented to provide a clear perspective on various aspects of the MCSRs to the researchers and engineers working in this field shows that there has been a significant increase in interest in MCSRs and associated control methods. This is due to increasing concern about power quality and the availability of suitable power-switching devices at affordable prices. Utilities are finding it difficult to maintain the power quality at the consumer end, and consumers are paying the penalties indirectly in the form of increased plant downtimes, etc. At present, MCSRs technology is well developed, The utilities in the long run will induce the consumers with nonlinear loads to use the MCSR's for maintaining the power quality at acceptable levels. A large number of MCSRs configurations are available to compensate harmonic current, reactive power, neutral current, unbalance current, and harmonics. To facilitate understanding and selection of particular configuration and control techniques for a given application, the classification is based on six main criteria. The power-circuit configurations of MCSRs and the ratings of the compensated systems define the three broad categories. The other three classification criteria are based on the control strategies, control techniques and reference-estimation methods generally employed. The review also takes into account the criteria for selecting passive components, and the switching frequencies and losses for the various configurations are also discussed. The manner in which the paper has classified the different aspects of MCSRs, although not providing a detailed analysis, should help research workers, users and suppliers of electrical power to gain an overview and inspiration for further research on this subject. It is obvious from the survey that a great deal more work still needs to be done; particularly as the problems associated with generation, transmission, distribution and consumption of power become more serious. The consumer can select the MCSRs with the required features. It is hoped that this survey on MCSRs will be a useful reference to the users and manufacturers.

Acknowledgement

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