# Reconfigurability, Modularity and Redundancy Trade-offs for Grid Connected Power Electronic Systems

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# Reconfigurability, Modularity and Redundancy Trade-offs for Grid Connected Power Electronic Systems

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***Abstract*—Power electronic converters (PECs) are workhorses of emerging distribution networks. PEC interfaced grids can function as flexible power corridors facilitating compact and efficient energy exchange between distribution generation, load and storage elements. Introducing adequate Reconfigurability, Modularity, and Redundancy (RMR) in such PEC-driven hybrid ac-dc distribution networks can enhance power delivery, thus enabling infrastructure savings. In this paper, an approach for implementing adequate RMR is introduced that can be applied at both converter- and system-level; therefore, the system's reliability can be improved. Furthermore, in this discussion, the impact of integrating renewable energy sources, charging stations and storage systems with the grids is considered with regard to the methodologies of applying RMR to improve the reliability. Potential applications include various power electronics converters, parallel ac-dc links, embedded PEC energy routers, dc hubs, and multi-parallel converter systems capable of regulating power flows between different nodes in the grid with fault-tolerant topologies.**

***Index Terms*—Reliability, Redundancy, Modularity, Reconfigurablity, Failure rate.**

## I. Introduction

In recent years, alongside the power electronics devices development [1], voltage source converters (VSC) such as modular multilevel converter (MMC), two-level converter (2L-VSC), three-level converter (3L-VSC) among other types, showed a significant increase of applications in power grids [2]. On the other hand, the penetration of distributed systems such as renewable energy sources (RES), charging stations, storage systems, etc., has risen considerably [3]. Additionally, due to population increase, the demand for electricity increases sharply, and the need for reliable power supply is apparent [4]. Therefore, there are growing number of installed electrical energy systems (load and supplier) that consequently increase the demand for reliable power systems to decrease the likelihood of blackouts [4].

It is of great importance to modernize the grid-connected power electronics systems to increase the system reliability and decrease the greenhouses gases emission by integrating RES, e-mobility technologies and storage units into the power systems [5], [6]. For such energy transition goals, the role of power electronics is pivotal in enabling grid integration with PECs as efficient and reliable interfaces [7], [8]. It is worth mentioning that grid-connected PECs such as meshed transmission systems with multiple terminals [9], including medium voltage and high voltage VSC-MTDC, are becoming an attractive solution due to their high-level controllability, power transfer capability, and operational flexibility [10]. But, utilization of more power electronic-based systems can pose challenges to reliable planning and operation of the system [6]. Furthermore, PECs are composed of many components, including power switches, capacitors, etc., which can be a source of failure and negatively affect the reliable operation of the power systems [11]. For instance, in grid-connected PECs, converters can contribute to unplanned downtime of RES where the cost losses are significant [12].

The reliability analysis is gaining attention in grid-connected PECs in which the reliability evaluation can be performed at component-level [5], [6], [13], converter-level [3], [9], [10], [14]–[18] and system level [4], [7], [19]–[24]. Study [10] evaluates the reliability and cost aspects of various converters, and it presents the impact of applying redundancy at the converter level; finally, based on the power rating, the optimal types of power electronics are proposed. In [3], [25], [26] the impact of redundancy on hybrid MMC is scrutinized. A detailed comparison among various types of redundancy strategies can be found in [14], [16]. In [18], the effect of modularity at the converter level for MMC is evaluated; according to the mission profile, an optimal level of modularity based on the power switch type, cost and reliability is proposed. In [27], the concept of converter-level reconfigurability to achieve fault tolerance for the neutral-point-clamped (NPC) converter with an extra flying capacitor (FC) leg is explored. In [28], [29], reconfigurable DC-DC converters and the principle of achieving fault-tolerance are explained. Also, a review of reconfigurability and redundancy are well explored in [30], [31]. Authors in [4], [23] investigated the reliability of the HVDC system, and they analyzed the impact of integrating PECs into the system by using different approaches. In [32], [33], reconfigurable systems are evaluated for scenarios where there is fault in one of the three phases of the transmission systems and the other two healthy phases behaving as a DC-link to transfer the power. In [7], [24], [34], the reliability of the power system with penetration of wind farms is evaluated.

Most of the studies regarding the reliability analysis at the converter and system-level only evaluate the reliability without proposing how to enhance the system's reliability. However, applying redundancy at the converter level for MMC is well explored, and various redundancy strategies such as active load-sharing, active fixed-level, and standby are proposed that significantly improve the reliability of MMC at the converter level [16]. For enhancing the reliability of the grid-connected PECs, redundancy, modularity, and reconfigurability (RMR) could be the solution. These three scenarios can be applied in designing, planning, and operation to improve the system reliability without extra cost or with a cost-efficient approach. Therefore, this paper gives an overview of how to implement RMR at both converter and system-level to increase the system reliability even if more and more PECs are connected to the grid.

The remainder of this study is organized as follows. Section II introduces how to implement RMR at the converter level to improve its reliability. In section III, the ways of implementing RMR at the system level will be explored, and section IV explains how the penetration of distribution systems can affect the reliability of the power systems and it proposes the possible solutions. Ultimately, the paper establishes a procedure for applying RMR in section V and it is concluded in section VI.

## II. RMR at Converter Level

This section gives an overview of implementing RMR at the converter level, focusing on the MMC; however, these concepts can be extended to any other types of converter. Additionally, it will be explained how to implement RMR to achieve reliable configuration for the converter. In the following sub-sections, the concept of RMR will be described and shown graphically for better understanding.

### A. Converter-level Modularity

Modularity is the degree to which system components might be separated in power converter applications, providing the system with flexibility and a higher number of choices for components selection. The modularity can be applied in MMC concerning the MMC's arm level and by considering the cost and reliability aspects. Therefore, optimal choices could be based on the number of levels and power switches rating. The characteristics of various switches determine the system's reliability, efficiency, and cost. For example, Fig 1 represents the MMC with two modularity scenarios which can be obtained by applying [35]:

$$k = ceil[\frac{V_{\mathrm{dc}}}{S_{\mathrm{f}} \times V_{\mathrm{IGBT}}}] = \left\lceil \frac{V_{\mathrm{dc}}}{V_{\mathrm{SM}}} \right\rceil, \tag{1}$$

where the safety factor $S_{\mathrm{f}}$ of 0.5 is considered. k is the minimum number of levels and $V_{\mathrm{IGBT}}$ is the IGBT blocking voltage . In the first case, if the voltage rating of the power switch is 1.7 kV, the number of arm level is 33. In the second case, if voltage rating of power switches is 3.3 kV, the applied level will be 17 .

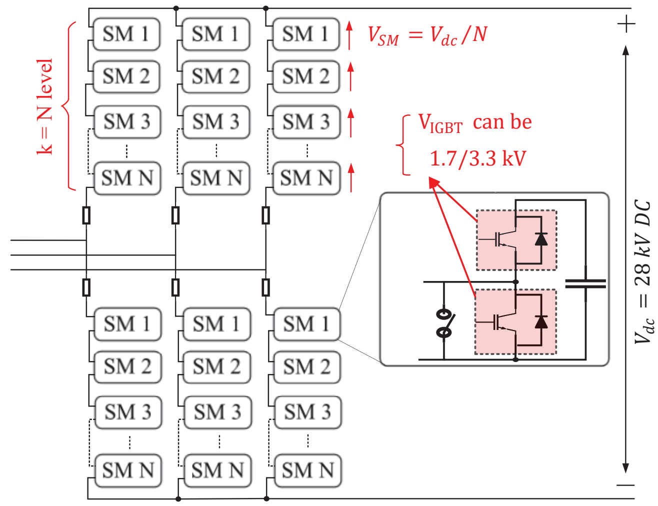


Fig. 1. The MMC general configuration with two modularity scenarios.

As shown from Fig. 1., there are many choices regarding the MMC modularity. Each modularity scenario has its advantages and disadvantages, and the optimal configuration can be selected based on assumptions, system requirements, reliability, cost, efficiency, etc. For instance, in Fig. 1., if N = 33, there is more sub-module (SMs) within the MMC compared to N = 17, and the reliability of such a system might be lower since there is a higher number of components and the chance of SM failure is more. Also, the efficiency of the MMC with N = 17 could be higher than N = 33 since there are a lower number of power modules and consequently, the lower conduction losses (higher efficiency) will be [14], [18]. However, the modularity of MMC with N = 33 gives higher flexibility and smoother modulation, that consequently decreases the harmonic distortion and filter size [35]–[37].

For a quantified comparison, consider the simplified reliability formulation of MMC based on Reliability Block Diagram (RBD) of MMC given by:

$$R_{\mathrm{MMC}}(t) = e^{-(2\lambda_{\mathrm{IGBT}}+\lambda_{\mathrm{cap}})\times 6kt} \tag{2}$$

where $\lambda_{\mathrm{IGBT}}$ = 0.003 occ/year and $\lambda_{\mathrm{cap}}$ = 0.001 occ/year are the approximate failure rate of IGBT module and capacitor respectively, estimated based on Military Handbook (MIL) [38]. $R_{\mathrm{MMC\text{-}0R}}$ in Table I indicates the reliability of the MMC for different switch ratings at the end of one year of operation without any redundant sub-modules. Increasing $k$ with reducing switch rating represents increasing modularity, which consequently reduces the converter reliability due to higher number of constituent components.

### B. Converter-level Redundancy

The simple definition of redundancy means the inclusion of additional components within the system's structure that are

TABLE I
RELIABILITY OF THE MMC AT THE END OF FIRST YEAR.

| | 1.2 kV | 1.7 kV | 3.3 kV | 4.5 kV | 6.5 kV |
|---|---|---|---|---|---|
| k | 47 | 33 | 17 | 13 | 9 |
| $R_{MMC\text{-}0R}$ | 0.14 | 0.25 | 0.49 | 0.58 | 0.68 |
| $R_{MMC\text{-}1R}$ | 0.765 | 0.870 | 0.961 | 0.976 | 0.988 |
| $R_{MMC\text{-}2R}$ | 0.972 | 0.989 | 0.998 | 0.9993 | 0.9998 |

not necessary to function, and they are used in case of other components' failure. So, redundancy is one of the approaches to embed the fault-tolerance ability within the system structure. The MMC is composed of SMs connected in series to reach the desired DC-link voltage. In this type of converter, to increase the converter reliability in case of SM failure and without degrading the post-fault operation, redundant SMs are used in the MMC as it is shown in Fig. 2.

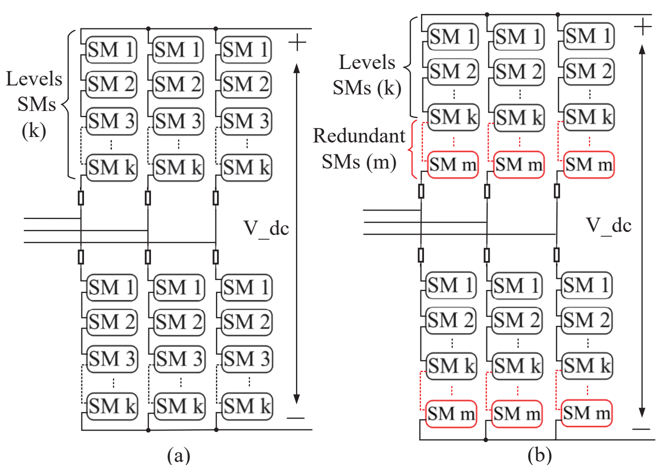


Fig. 2. The MMC configuration with (a) and without (b) redundant SM.

Regarding the operation of MMC with redundant SM, various strategies such as active load-sharing, active fixed-level, and standby are proposed wherein each strategy; the redundant components can be operational or remain idle. For example, in the non-redundant configuration of Fig 2 (a), if any one of the SMs within the MMC fails, the converter should shut down (or, in some cases, it can operate at a derated power) whereas, in a redundant configuration, if an SM fails (open circuit or short-circuit) it can be bypassed. As a result, the converter continues to operate at the rated power [14]. Equations (4) and (5) is used for calculating the reliability of MMC with standby redundancy.

$$\lambda_s = (2\lambda_{IGBT} + \lambda_{cap}) \times k \tag{3}$$

$$R_{arm}(t) = \sum_{i=0}^{n-k} \frac{(\lambda_s t)^i}{i!} e^{-\lambda_s t} \tag{4}$$

$$R_{MMC}(t) = (R_{arm}(t))^6 \tag{5}$$

where, $\lambda_s$ is the arm failure rate and $n = k + n_{red}$ is the total submodules including redundancy $n_{red}$ per arm. $R_{MMC\text{-}1R}$ and $R_{MMC\text{-}2R}$ in Table I indicates the reliability of the MMC for different switch ratings at the end of one year of operation with $n_{red} = 1$ and $n_{red} = 2$, respectively. It can be observed that the converter reliability significantly improves with increasing $n_{red}$, with $R_{MMC\text{-}2R}$ being above 95 % for all switch ratings. At the same time, the cost of a single redundant SM is lowest for lower switch rating.

### C. Converter-level Reconfigurability

In general, the ability of the system to rearrange its various parts in case of failure is called reconfigurability. This is another way of meeting fault tolerance capability. The reliability of the converter can be improved if reconfigurability is embedded within its structure [27] that in some cases is compulsory such as off-shore wind turbines where maintenance could be challenging and not cost-efficient [39]. Hence, reconfigurability is required to increase the system reliability and availability. For example, in [40], a three-level neutral-point-clamped (NPC) converter with an extra flying-capacitor (FC) is proposed, wherein in case of fault, the FC leg will take over, and the converter continues its operation. Other examples of the reconfigurable converter are presented in [28], [29] in which reconfigurable DC-DC converters are proposed to embed the fault tolerance within their structures.

It is worth mentioning that fault tolerance ability in various converter topologies has been explored in which, the converter is fault-tolerant because of applying redundancy or/and reconfigurability. There are two ways of reaching fault tolerance ability that is redundancy and reconfigurability; However, there is a distinction between redundancy and reconfigurability. In redundancy, the configuration of the converter after a fault and before a fault is identical; whereas, in reconfigurability, the post-fault structure of the system is different than before fault occurrence [28], [29], [31], [40]–[42].

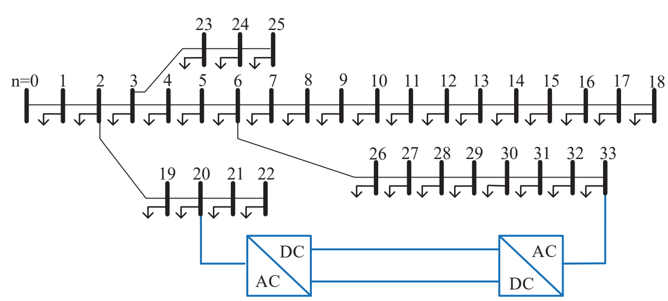


Fig. 3. The scheme of 33-bus system with reconfiguration ability using back-to-back PE converter.

## III. RMR AT SYSTEM LEVEL

Similar to converter-level RMR, the concept of RMR can be extended for grid-connected power electronics systems. Moreover, applying RMR at the converter level impacts system-level reliability. For example, in [9], the effect of the applied redundancy at the converter level is analyzed, and it is shown that the system-level reliability has improved. However, the

RMR is only evaluated at the system level in this part. It is assumed that sub-parts of the system, such as converters, have a constant failure rate regardless of whether the RMR is applied at the converter level or not.

### A. System-level Reconfigurability

System-level reconfigurability is a newly addressed topic, and there is limited literature addressing it. However, reconfigurability at the system level can embed the fault tolerance within the system's structure, and grid-connected PECs with reconfigurability can withstand (n-1) contingencies. In [43], the system transfers power through a 3-phase transmission system in regular operation. In case of one of the transmission lines outage, the two remaining transmission lines and integrated power electronics converter ensure the power transfer [43]–[45]. Another example is the 33 radial bus system shown in Fig 3, a standard radial AC system in many countries. For instance, if one part of the radial AC system is out of order, the remaining healthy parts will also be disconnected. Hence, it is proposed to use a back-to-back power converter to reconfigure the radial system into a mesh system. Therefore, if one part fails, the healthy parts will remain connected, and power can transfer through the back-to-back power converter.

### B. System-level Modularity

Modularity can be applied in a grid-connected PECs such as converters, transmission lines, transformers, etc. Therefore, the optimal configuration could be selected based on the cost, reliability, efficiency, etc. For instance, in [4], [23], the sending and receiving-ends of the back-to-back converters are composed of two sets of transformers, converters, filters, and breakers in which every set caries out 0.5 p.u of the total power transfer. However, in [4], [23], the sending- and receiving-ends of the system can be designed with one converter at each ends, hence, they transfer the total power (1 p.u).

Depending on the modularity of different system parts, the reliability, efficiency, cost, etc., can vary, and one can select various options based on the system requirements.

### C. System-level Redundancy

System-level redundancy is another approach for increasing system reliability, but it is incorporated with a cost increase, and cost efficiency plays a vital role at the system level. Like system-level modularity, redundancy can be applied to different parts such as converter, transformer, transmission lines, bus bars, etc. In [21], the redundancy is used at transmission lines in which 2-out-of-3 of the transmission lines are required. The additional line will start to operate in case of one of the transmission lines outage. Another example is the Multi-terminal HVDC system (MTDC) system with double bus-bar double-breaker [46] that in case of one of the bus-bars failure, there is an extra bus-bar to ensure the operational continuity. System-level redundancy is also an essential concept for uninterruptible power suppliers (UPSs) [47] that is shown in Fig 4 where a redundant system is used to ensure the operational continuity in case of one system failure. Moreover, applying the redundancy concept for driving the motor is well-known in which two converters are used; in this case, if one of the converters fails, it will be blocked, and the healthy converter takes over [31].

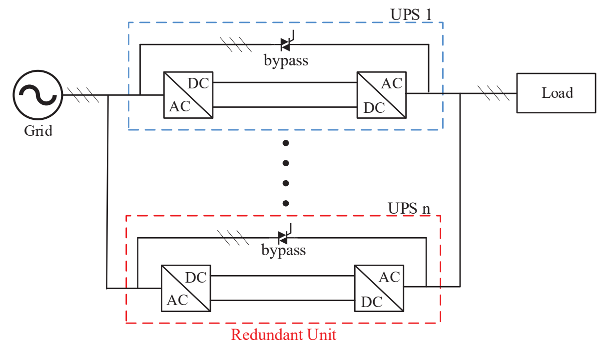


Fig. 4. Configuration of redundant UPS systems.

Redundancy incorporates extra components that increase investment costs (or operational losses). Nevertheless, it can substantially increase the system's reliability, and it could be cost-efficient in the long term. Moreover, redundancy ensures operational continuity in case of fault or failure. Therefore, system-level redundancy can be justified since there is an equilibrium between reliability and cost.

## IV. Integration with Distribution Systems

Modernization of power systems incorporates the interconnection of distributed systems such as renewable energy sources (RESs), charging stations, storage units, etc. [5]. For power systems modernization, due to their ability to move towards low-zero carbon footprint, the importance of PEC's have significantly intensified [8], [22]. However, as explained above, the PECs are one of the significant sources of failure that impacts the reliability of the grid-connected PECs. Integration of distribution systems through PECs changes the system reliability and availability; hence, it requires in-depth investigation. For instance, in [9], integration of a 600 MW wind farm into an RTS-24 system through a MTDC is evaluated, and it shows how the reliability indices can be improved. In [11], the reliability of low voltage grid-connected PECs is evaluated, and the vulnerable parts are identified by carrying out the reliability analysis. The reliability of 33 bus system in the presence of several distribution systems at various buses that can be evaluated as shown in Fig. 5. Distribution systems such as charging stations and RESs can be integrated. Hence, distribution system integration affects the system's reliability due to the usage of PECs and change of loading and generation. Therefore, the same approach of applying RMR at the converter and system levels can be taken to improve the reliability of such a system.

## V. The Procedure for Implementing RMR

The concept of RMR can be applied to any converter and system; this can be seen from Fig. 6. for MMC at the converter-level and 33-bus system at the system level with and

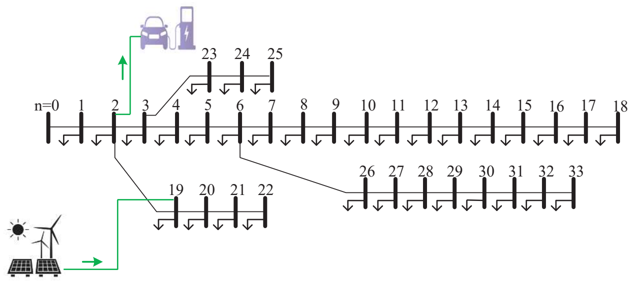


Fig. 5. Configuration of 33-bus system in presence of distribution systems.

without distribution systems. However, Fig. 6. is an example of applying RMR at the converter- and system-level; it can be extended for any converter and system. For instance, for the system shown in Fig. 4., to increase the reliability, redundancy is applied, or for improving the reliability of the converter presented in [40], reconfigurability is used to increase the NPC converter reliability. So, there is not a specific approach to applying RMR, and it could differ for various systems.

Therefore, to improve the reliability of a specific system, there are several steps to take that are as follows:

- **Step 1:** Identifying reliable design of PECs by implementing RMR for different types of converters. In this stage, efficiency, cost, and reliability are critical factors in choosing an optimal converter design.
- **Step 2:** In this step, firstly, a benchmark network should be selected, which is well explored, and the reliability data for such a system is available. Then, nodal reliability is carried out to identify the crucial nodes. At this stage, the target is to improve the system's reliability. For instance, the system can be changed from radial to meshed by using a back-to-back DC-link. Hence, the reliability of the system will improve. In this stage, several facts need to be considered that are addressed as follows:
  – Determining the optimal PECs to be used.
  – If the RMR is applied at converter-level, identifying their effect on the grid-connected PECs is essential.
  – Nodal reliability can be applied to determine the critical nodes and find the optimal RMR scheme.
- **Step 3:** In the final stage, the distribution system will be integrated. For example, in 33-bus system shown in Fig. 5., integration of load/generation can occur at different nodes. Therefore, in this phase, a guideline could be proposed for applying RMR at the system level in the presence of distributed systems.

## VI. Conclusion

In this paper, an introduction to redundancy, modularity, and reconfigurability is given. It is explained how RMR can be applied at both converter- and system levels. The concept of using RMR at the converter level is developed with a focus on MMC. It presents how the reliability and availability of the PECs can be improved. Then, the big picture of applying RMR at the system level is provided. It was shown that the approach to use RMR is different for different systems. For instance, for the 33-bus system presented above, reconfigurability could be a feasible solution to improve system reliability. In the case of UPSs, system-level redundancy is an optimal choice. In addition, it was shown that integration of distributed systems mainly through PECs is challenging since it affects the entire system's reliability. Therefore, applying RMR at both converter and system-levels can solve this problem. This study provides us with an approach that uses redundancy, modularity, and reconfigurability at both converters- and system levels (with and without penetration of distributed systems) to improve the system reliability.

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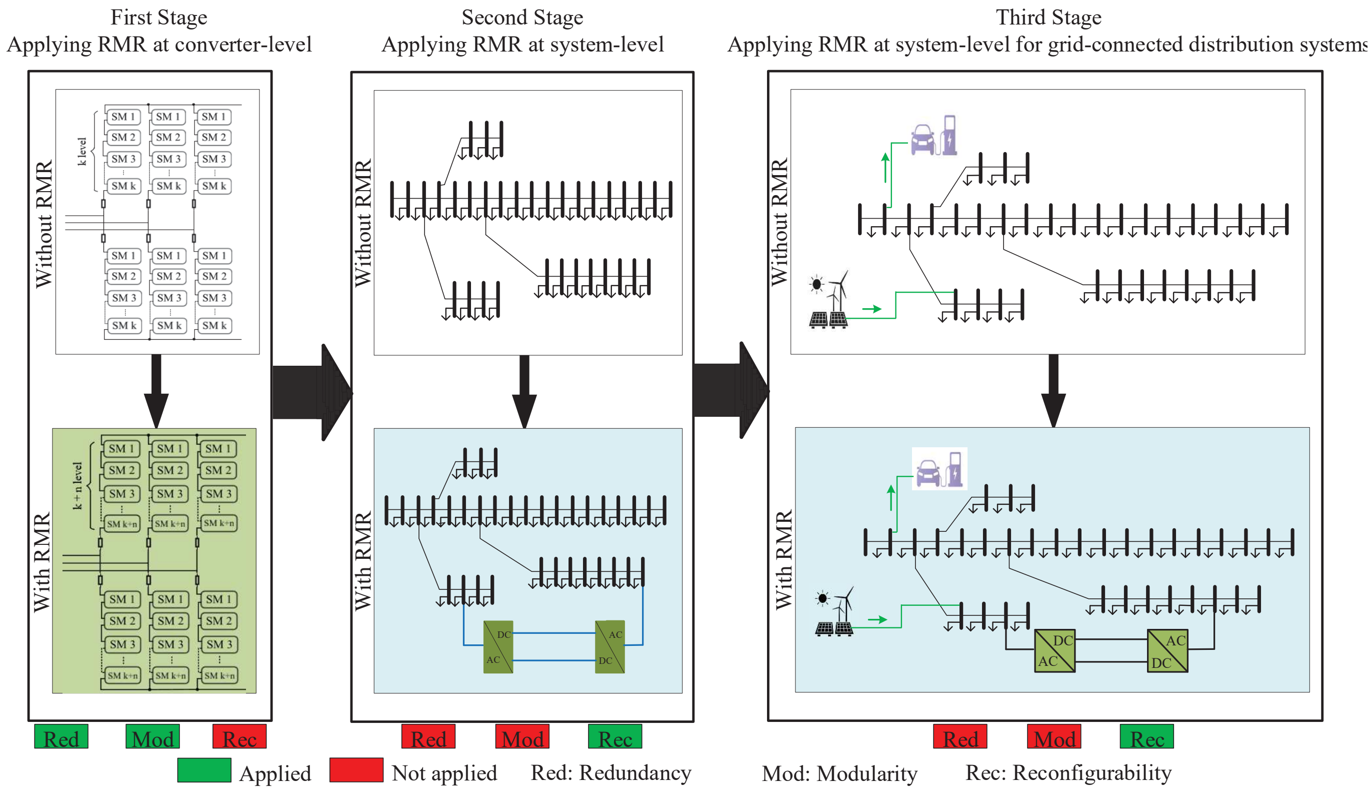


Fig. 6. Example of applying RMR at different stages.

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