Letters

Modularized Diode Rectifiers: A New Family of Solid-State Transformers

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***Abstract*—Solid-state transformers (SSTs) are conventionally based on a multistage architecture, with an input and/or an output ac/dc converter (for interfacing with the ac grid and/or the load), and with an isolated dc/dc conversion stage (to provide insulation and voltage/current scaling). Alternatively, some single-stage SST circuits use ac/ac conversion modules and rely on bidirectional blocking devices, which however have limited commercial availability and face significant operational challenges. This letter explains the derivation, operating principle, and fundamental topologies of a new family of SSTs, named modularized diode rectifiers. Their architecture is derived from the integration, within basic diode rectifier circuits, of dc/dc converter modules, which are fed by unipolar pulsating voltages. Despite using only dc/dc modules, this family of circuits can achieve isolated ac/dc and/or ac/ac conversion, can provide power factor corrector features, and can be easily scaled for higher voltage and/or current ratings.**

***Index Terms*—Isolated power conversion, modularized diode rectifiers (MDRs), solid-state transformers (SSTs).**

I. INTRODUCTION

SOLID state transformers (SSTs) are advanced power converters designed to replicate the same features of conventional transformers, such as voltage/current scaling and galvanic insulation, while also providing enhanced controllability and flexibility through power electronics conversion circuitry, and extending their applicability also to dc systems. Furthermore, SSTs can be operated at high frequency, which can help in reducing size and weight of magnetic components and filters, resulting in higher power density compared to conventional low-frequency transformers [1]. For these reasons, their implementation is becoming increasingly attractive in many emerging application fields, such as electric vehicle charging stations, renewable energy generation plants, electrolyzers, data centers, and smart grid/smart cities.

To achieve ac/dc and ac/ac conversion, standard SST architectures typically include an input ac/dc stage, an isolated dc/dc block operating at high frequency and, eventually, also an output dc/ac stage. When interfacing systems at medium voltage levels, multiple identical conversion modules are often used to realize multicell conversion topologies or input-series/output-parallel (ISOP) configurations.

A significant drawback of conventional SST designs is their high system complexity, which arises from the presence of multiple conversion stages, each requiring its own sensors, gate-driving circuits, control, and protection mechanisms. For these reasons, SSTs are still not fully commercialized, despite numerous prototypes and demonstrators being reported.

Some SST architectures based on single-stage ac/ac modules are also well known in the technical literature [1]. However, they rely on semiconductor switches with bidirectional voltage blocking capabilities (which are not commercialized as standalone components and are typically realized by connecting two unidirectionally blocking devices in antiseries), which also leads to significantly complex architectures and is impacted by significant operational challenges.

However, a new family of SST conversion circuits is recently emerging in the power electronics community. These converters, here named modularized diode rectifiers (MDRs), are realized by integrating isolated dc/dc modules into the architecture of basic diode rectifier circuits. Contrarily to standard SST architectures, the dc/dc modules in an MDR are connected to the ac supply without any ac/dc conversion stage, but are operated from pulsed unipolar input voltages. Therefore, they do not require bidirectionally blocking devices and can be realized with conventional dc/dc topologies. Furthermore, by controlling the power transfer between the primary and secondary side, they can not only provide isolated high-frequency conversion, but also power factor correction (PFC) functionality and power flow control.

Only very few MDR examples have been introduced in the past few years, separately emerging from different industrial patents [2], [3], with some preliminary analysis [4], [5], control strategies [5], [6], [7] and comparative evaluations [8] being recently presented to complement and support them.

However, so far, the MDRs are still obscure and little known in the technical community, despite their very interesting and unique operating principle. Therefore, this letter presents and discusses the derivation, operating principle, and fundamental topologies (both single-phase and three-phase) of this new family of SST converters, and briefly presents currently open challenges and potentialities of such conversion structures.

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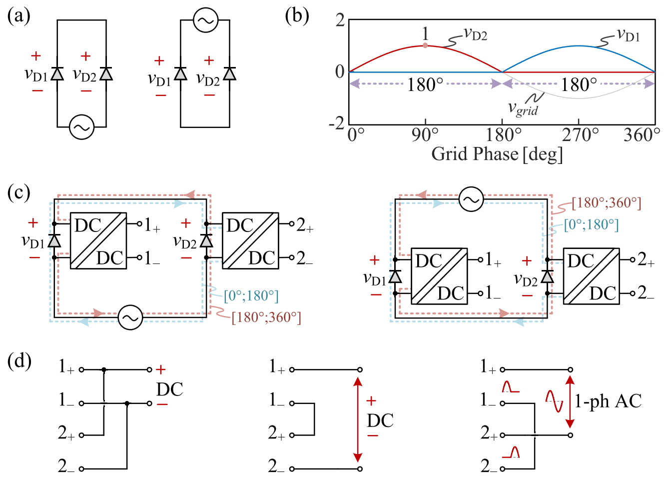

Fig. 1. Derivation of the MSPR. (a) Nonfunctional circuit with two antiseries connected diodes (with either common cathodes or common anodes). (b) Cathode–anode voltages of the two diodes. (c) Connection of the DC/DC modules to the basic circuit. (d) Different possible configurations of the secondary-side connections.

II. Derivation of Fundamental MDR Topologies

A. Modularized Single-Phase Rectifier

The derivation of a modularized diode rectifier can be most simply explained starting from the circuits represented in Fig. 2(a). These circuits consist of two diodes connected in antiseries (with a common terminal that is either at their cathodes or at their anodes), and connected to a single-phase ac supply. In this basic configuration, no current can flow through the system since, depending on the polarity of the ac grid voltage, only one of the two diodes would be conducting, while the other would be in blocking state. However, from this basic and nonfunctional circuit, it can be noted that the cathode–anode voltage of each diode is a unipolar pulsed waveform, which is equal to the positive half-sine wave of the ac supply for 180° of the ac grid period, and is zero for the remaining 180°, as illustrated in the simplified diagram of Fig. 2(b).

Thanks to the unipolar nature of this pulsed voltage, an isolated dc/dc converter module can be directly connected in parallel to each diode, as depicted in Fig. 2(c). Then, when one of the diodes is blocking, its anode–cathode voltage is positive, and the corresponding dc/dc module can be controlled to transfer a desired power to the secondary side. In this case, the ac grid current can flow through the controlled dc/dc module and through the other diode of the circuit (which is conducting), and the previously nonfunctional circuit can be made operational. With reference to the two 180°-wide intervals of Fig. 2(b), the paths of the ac grid current in the circuit are represented by the dashed lines in Fig. 2(c).

Therefore, through this circuit configuration, here named modularized single-phase rectifier (MSPR), a single diode is effectively replacing the role of an entire ac/dc stage. Then, depending on the configuration of the secondary-side connections and on the control of the dc/dc stages, either a dc or an ac output can be provided, as exemplified in Fig. 2(d). Then, according to the desired type of conversion for the overall MSPR, the conversion modules should either be controlled with a fixed or with a varying voltage gain.[1] If the currents of the dc/dc modules are properly shaped as half-sine waves, the MSPR can also intrinsically provide PFC functionality, while a desired voltage/current scaling can be easily obtained through the transformation ratio within the isolated dc/dc stages. However, since the dc/dc modules are only operated for 50% of the time, each of them must be able to process the power required by the secondary-side load. This means that the total power processing capacity installed in the system needs to be twice the full load power.

B. Modularized Star Rectifier

An immediate extension of the MDR circuit for a three-phase supply is depicted in Fig. 1(a), and is based on three diodes arranged in a star configuration, connected either at their cathodes or at their anodes. In this configuration, first proposed in [2] and [4] and here named modularized star rectifier (MSR), only one out of the three diodes is conducting at any given time, while the other two are blocking. Consequently, the cathode–anode voltage across each diode is again a unipolar pulsed waveform, and the three parallel-connected dc/dc modules can transfer power during the blocking state intervals.

However, in the MSR configuration the cathode–anode voltage of each diode is positive for 240° and zero for the remaining 120° of the ac grid period, as shown in Fig. 1(b). This means that two out of three dc/dc modules can be used at the same time, cycling every 120°.

Similarly to the previous example, also for the MSR, depending on the circuit configuration on the secondary side, it is possible to generate either a dc output (using either a series or a parallel connection between the three secondaries), or an ac output (e.g., using a star-connection of the three secondaries, as proposed in [4]). This is exemplified in Fig. 1(c).

Compared to the MSPR, the simultaneous use of two modules in the MSR helps to provide better power sharing among the dc/dc stages, which need to process only half of the load power, each. Nevertheless, all the diodes and the dc/dcs need to be able to withstand the full line-to-line ac voltage.

C. Modularized Bridge Rectifiers

A further extension of the MDR circuits discussed so far is represented by the bridge topologies shown in Fig. 3(a) and (b), respectively, derived from the single-phase and three-phase topologies of Figs. 2 and 1, and here referred as modularized bridge rectifiers (MBRs).

For the single-phase MBR architecture, shown in Fig. 3(a), the circuit is obtained by combining the two MSPR circuits of Fig. 2(c), and is equivalent to integrating dc/dc modules into a

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[1] In general, for ac/dc conversion, the dc/dc modules should be controlled to transfer power from a primary-side with pulsed voltage to a secondary-side with an almost constant voltage (i.e., operating with a varying voltage gain). Instead, for ac/ac conversion, the dc/dc stages should be controlled to generate at their secondary-side a scaled replica of their primary-side voltages (i.e., operating with a fixed voltage gain), in a way to obtain the desired ac output at the secondary-side terminals.

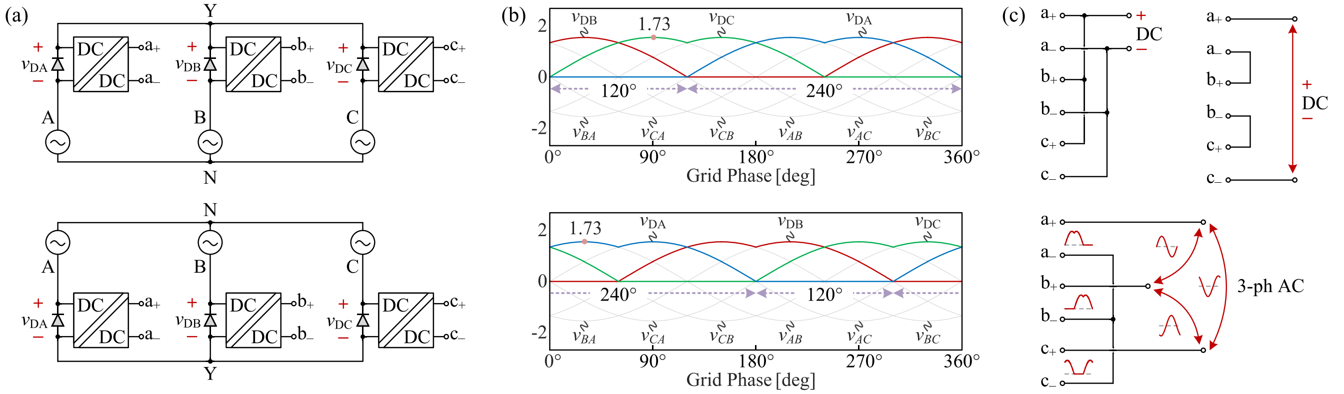

Fig. 2. Topology and operation of the MSR. (a) Circuit architecture. (b) Cathode–anode voltages of the three diodes (both in case of common cathode and common anode configuration). (c) Different possible configurations of the secondary-side connections.

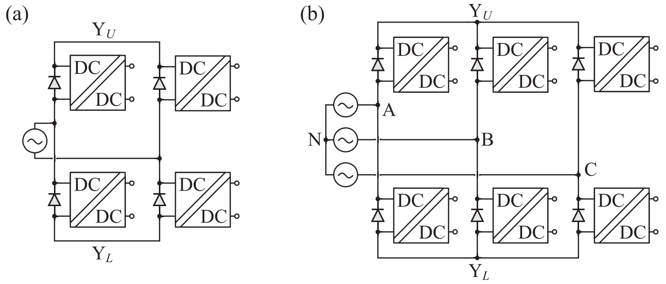

Fig. 3. Topology of the MBR. (a) Single-phase architecture (obtained by combining two MSPR circuits). (b) Three-phase architecture (obtained by combining two MSR circuits.)

standard single-phase diode bridge rectifier. The operation of the single-phase MBR is similar to the MSPR circuit described earlier, with the only difference being that in each 180°-wide interval two diodes are in conduction and the other two are in blocking state, meaning that two out of four dc/dc modules can operate simultaneously and share the power of the load.

For the three-phase MBR architecture, first introduced in [3] and here shown in Fig. 3(b), the circuit is derived by combining the two MSR configurations shown in Fig. 1(a). In this circuit, at any given time, only one diode is conducting on the upper star (the diode corresponding to the maximum instantaneous ac phase-to-neutral voltage), and only one diode is conducting on the lower star (the diode corresponding to the minimum instantaneous ac phase-to-neutral voltage). This means that four diodes out of six are in blocking state at any instant of time, allowing the corresponding dc/dc modules to transfer power to the secondary side. However, unlike the MSR configuration, in this case the conducting and blocking branches of the circuit are cyclically changing every 60° of the fundamental ac grid period. This is due to the 60° phase shift between the voltages in the upper and lower stars of the MBR, which follow the same waveforms of Fig. 1(b).

The presence of six dc/dc modules, each of which operated for $2/3$rd of the period, allows to further reduce the power to be processed from each module, that can be sized for $1/4$th of the load power. Moreover, the presence of multiple branches and of recirculating paths also allows for the definition of different control strategies to redistribute the instantaneous power flow among the integrated dc/dc modules, enabling the development of optimized control approaches [5], [6]. However, similarly to the MSR, also in this case the diodes and dc/dcs need to withstand the full line-to-line ac voltage.

III. EXTENSIONS, CHALLENGES, AND OPPORTUNITIES

From the examples presented in the previous section, it is evident that a common feature of the MDR topologies is that they all operate by performing ac/dc or ac/ac conversion using only dc/dc modules, driven by unipolar pulsed input voltages. By following this approach, various circuit extensions can be derived, further expanding this emerging family of SST architectures. Some other aspects of their general design and operating characteristics are discussed in the following.

A. *Installed Power Processing Capacity*

Considering a fundamental ac period, the power required by the load is, on average, equally shared by all the dc/dc modules of any MDR topology. However, since the conduction interval of the dc/dc modules does not cover the full 360° cycle, not all the installed modules can be utilized at the same time. This means that each module must be able to process a higher power during its limited conduction interval. As a result, the overall installed power processing capacity in an MDR is inherently higher than the power required by the load. For this scope, Table I provides a short summary of the average power processing requirements for the fundamental MDR topologies discussed in the previous section. This oversizing requirement is an intrinsic limitation of the MDR structures, and comes as an unavoidable tradeoff from the absence of any ac/dc and dc/ac stage (that would be instead required in standard multistage SST architectures) and of any ac/ac stage (that would be required in single-stage SST architectures based on bidirectionally blocking devices).

However, since the power is directly transferred from the primary to the secondary side through a subset of the installed dc/dc

TABLE I
KEY PARAMETERS OF THE FUNDAMENTAL MDR TOPOLOGIES

Parameter	MSPR	MSR	MBR (1-ph)	MBR (3-ph)
Number of modules	2	3	4	6
Number of active modules	1	2	2	4
Conduction interval	180°	240°	180°	240°
Average power per module (in a fundamental period)	$\frac{P}{2}$	$\frac{P}{3}$	$\frac{P}{4}$	$\frac{P}{6}$
Average power per module (in the conduction interval)	P	$\frac{P}{2}$	$\frac{P}{2}$	$\frac{P}{4}$
Installed power capacity	$2P$	$\frac{3P}{2}$	$2P$	$\frac{3P}{2}$

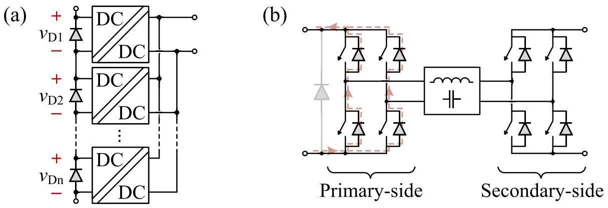

Fig. 4. (a) ISOP configuration for an MDR branch. In this case, the DC/DC modules are also responsible for the voltage sharing among the n units. (b) Topology of a DC/DC module. The primary-side diode can be omitted and its role can be performed by the existing free-wheeling diodes.

modules operating concurrently, the higher installed power capacity does not compromise the conversion efficiency (contrarily to multistage SST structures, where the different conversion stages operate in cascade to one another).

Similarly, the higher power processing requirement does not necessarily correspond to a more expensive system design compared to standard SST architectures. Indeed, the MDR architectures eliminate the cost of the ac/dc, dc/ac, and/or of bidirectionally blocking devices, together with the corresponding auxiliary circuits (e.g., for sensing, protection, gate driving, control, etc.), which can potentially lead to a more cost-effective system. In addition, the MDR SSTs only require one kind of power electronics building block, and their implementation can benefit from economy of scale [8].

B. Input-Series/Output-Parallel MDR Branch Design

When interfacing systems at medium or high voltage, the voltage blocking requirements of the structure may exceed the capabilities of a single diode or dc/dc module. In such cases, multiple units can be connected in series. Then, the dc/dc modules would not only operate to transfer power between the primary and secondary side, but they would also work to ensure proper voltage sharing among the series-connected units [5], [8]. Similarly, if the current requirements exceed the capacity of a single diode or dc/dc module, multiple units can be connected in parallel. This approach allows implementing ISOP configurations, as in Fig. 4(a), and can be used to achieve higher voltage and/or power ratings.

C. Architecture of the DC/DC Modules

Unlike other single-stage SST topologies, the input and output voltages in the modules of an MDR SST are intrinsically unipolar, meaning that there is no need to adopt devices with bidirectional voltage blocking capabilities. On the contrary, standard galvanically isolated dc/dc architectures can be employed as modules for all MDR architectures.

Similarly to other SST architectures, the isolated dc/dc converters can be designed to operate at frequencies significantly higher than the ac grid, thereby reducing the volume and weight of the passive components.

To improve the conversion efficiency, resonant or dual active bridge topologies can be employed, taking advantage from their soft-switching characteristics. Considering the high efficiency that can be normally achieved for these dc/dc architectures, their employment would make it possible to reach very high conversion efficiency also for the overall MDR-SST structures (even around $98\% \div 99\%$).

For unidirectional designs, the secondary-side switches can be replaced by simple diodes or by devices operated as synchronous rectifiers. In addition, as exemplified in Fig. 4(b), if the dc/dc modules incorporate free-wheeling diodes (as is common in many topologies), they can be used instead of the external diodes explicitly shown in the previous schemes, thereby further simplifying their circuit [4], [5].

However, the dc/dc modules must operate with significantly varying input and/or output voltages and power flows. Therefore, conventional design approaches and control algorithms, which typically refer to constant waveforms, may be suboptimal for the operation in MDR architectures.

Thus, this opens new research directions both for both design and control addressing these unique operating waveforms.

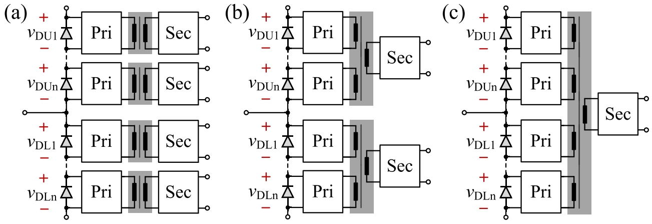

Fig. 5. Examples of magnetic integration for an ISOP MDR. (a) No integration. (b) Integration over a branch. (c) Integration over a phase.

D. Magnetic Integration

Considering the presence of multiple dc/dc converters, the high-frequency magnetic components of different modules can be combined with one another, with the aim to enhance the power density or the efficiency of the structure. Some possible examples are shown in Fig. 5. The analysis and comparison between different magnetic integration designs is also an open problem and allows for different optimization criteria.

E. Multiport Operation

A potential benefit of the MBR configurations, as shown in Fig. 3(a) and (b), is the possibility to directly interface also a dc source between the upper star node Y_U and the lower star node Y_L, intrinsically enabling the system to be used for

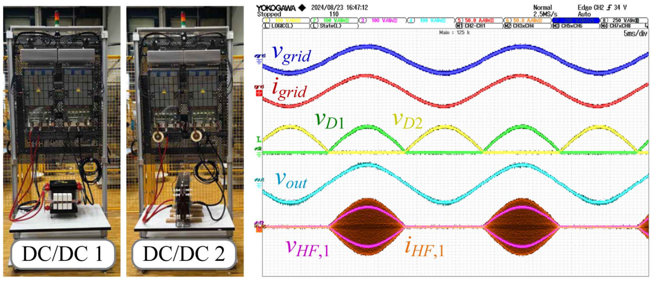

Fig. 6. Experimental prototype of an MSPR, configured as a single-phase AC/AC SST. (Left-hand side) DC/DC modules. (Right-hand side) Experimental results.

TABLE II
PARAMETERS OF THE DC/DC MODULES IN THE EXPERIMENTAL SETUP

Parameter		Value (SRC 1)	Value (SRC 2)
Resonant inductance	L_r	11.6 µH	9.5 µH
Resonant capacitance	C_r	37.5 µF	37 µF
Magnetizing inductance	L_m	750 µH	1100 µH
Turns ratio	$N_1 : N_2$	1 : 1	1 : 1
DC-bus capacitance	C_{DC}	50 µF	50 µF
Switching frequency	f_{SW}	10 kHz	10 kHz

a multiport conversion. However, if the dc source is directly interfaced between Y_U and Y_L, its voltage would need to be greater or equal to the peak line-to-line ac grid voltage. Under these conditions, the primary-side circuit of the system would operate similarly to an modular multilevel converter (MMC), resulting in increased voltage blocking requirements for the system components and requiring the dc/dc modules to operate with strictly positive voltages. In addition, the control algorithm for the structure should explicitly consider the different power flows toward the multiple ac and/or dc ports.

IV. EXPERIMENTAL VALIDATION

To practically demonstrate the operation of an MDR SST, an MSPR setup has been realized by connecting two diodes in common anode configuration [as shown in the right diagram of Fig. 2(c)] and by using, as integrated dc/dc modules, the two isolated series-resonant converters (SRCs) shown in Fig. 6, whose parameters are reported in Table II. The MSPR has been supplied by the 50 Hz grid by means of a variac, while the secondary sides of the two SRCs have been connected in antiseries [as in the last diagram of Fig. 2(c)] to realize a single-phase ac output, which has been used to supply a resistive load. The two SRCs have been modulated in open loop in subresonant operation, by switching their primary sides with a 50% duty cycle, with the aim to generate at their secondary sides a replica of their respective primary-side voltages (i.e., operating with a fixed voltage gain, equal to 1).

The experimental results are shown in the oscilloscope capture of Fig. 6, obtained for a 60 V input voltage and for a 1 kW supplied power. As can be seen, the diode voltages follow the same waveforms of Fig. 2 and, when the diode of the first branch is blocking ($v_{D1} > 0$), the corresponding SRC can transfer power to the secondary side, as confirmed by the presence of the high-frequency (10 kHz) voltage and currents in the resonant tank ($v_{HF,1}$ and $i_{HF,1}$). The diode and dc/dc module of the second branch are subject to complementary waveforms in the other 180°. As can be noted, in this configuration, the MSPR output voltage v_{out} and the current i_{grid} absorbed from the ac grid are also sinusoidal waveforms, and both of them are in phase with the ac grid voltage v_{grid}.

V. CONCLUSION

This letter presented the theoretical derivation and the operating principle of a new family of SSTs, named MDRs. The architecture of these structures is based on the integration of isolated dc/dc modules within the architecture of basic diode rectifier circuits. These dc/dc modules, which are operated from a unipolar pulsed voltage, can provide isolation, controlled power transfer, and voltage/current scaling between the primary and secondary. Compared to other conventional SST architectures, the MDRs require fewer conversion stages and do not need the use of bidirectionally blocking switching devices, thereby reducing the overall system complexity. Furthermore, they offer advantageous scalability for ISOP configurations and are well suited for magnetic integration and multiport operation. However, this comes at the expense of higher ratings for the dc/dc modules, which need to operate with a wide voltage range and that only work for a limited interval during each fundamental period, thus requiring higher power processing capabilities. Thanks to their reduced system complexity, MDR-based SSTs can find potential applicability in many emerging application fields, such as electric vehicle charging stations, renewable energy generation plants, electrolyzers, data centers, and smart grid/smart cities.

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