WHITE PAPER

Electrical protection and control for doubly-fed wind turbines

ABB coordinated solutions

Wind power plants and RES

Recent attention to climate change, demand to increase green energy capabilities, and awareness of the limited availability of fossil fuels have promoted a renewed interest in the production of electrical energy from renewable sources, including from wind power.

However, wind power has always provided propulsive force for sailing ships and running windmills. Then, this type of energy fell into disuse due to the wider use of electric power and thanks to the availability of machines supplied by low-cost fossil fuel.
With respect to other renewable energies, this type of energy uses a natural energy source that is usually available everywhere, particularly usable in temperate zones, where most industrialized countries are located.

During the last decade of the Twentieth century, different models of wind turbines were built and tested:
- **with vertical and horizontal axes**
- **with variable number of blades**
- **with the rotor positioned upstream or downstream of the tower, etc.**

Another classification distinguishes fixed speed wind turbines and variable speed wind turbines.

The advantage of variable wind speed turbines is that they always run close to their optimal working point (maximum energy efficiency), and therefore they are preferred over constant speed wind turbines. At least in principle, there are different solutions that allow the rotor to run at variable speeds, also maintaining constant frequency.

The most common are electrical solutions, in particular when using one of the following configurations:
- wound rotor asynchronous generators with external variable resistor
- wound rotor asynchronous generators with a power converter interposed between rotor and grid (doubly-fed configuration)
- asynchronous or synchronous generators with an electronic power converter interposed between stator and grid (full converter configuration).

Doubly-fed electrical drive generators are one of the most interesting of all the solutions.

The main advantages of doubly-fed electrical drive generators are the following:
- Energy production is increased thanks to variable speed operation
- Control of rotor voltages and currents enables the turbine to remain synchronized with the grid, while the wind turbine speed varies
- The turbine can continue to produce power even during lower wind speeds
- Lower cost due to the use of a small converter, one-third of the rated power
- Possibility to supply reactive power for grid support, with good voltage and power factor control
- High total system efficiency
- Technical and economical solution for grid code compliance

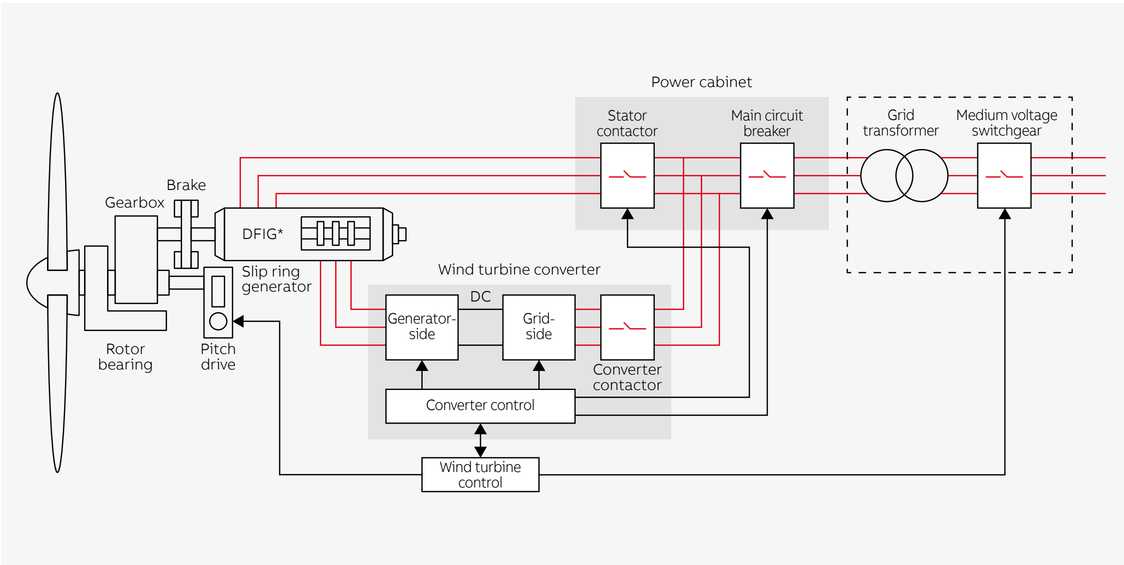
Wind turbines with doubly-fed generators

The doubly-fed concept gets its name from the fact that the generator feeds power from both the generator's stator and rotor: two-thirds of nominal power from the directly connected stator and one-third from the rotor.

The doubly-fed drivetrain concept uses an asynchronous generator with a wound rotor. The rotor windings are connected to a small converter using slip-rings and brushes. The converter is used to control the generator's speed and power factor, allowing a broader speed range for power production and the ability to feed reactive power to support the grid.

In case of wind speed that is lower or higher than the rated speeds, the converter will compensate these differences, feeding or removing power by the rotor.

Usually, the converter is sized up to one-third of the nominal power and therefore enables a speed range up to +/-30% of the rated speed.
Inside the converter, a DC-link capacitance circuit connects the DC-terminals of the grid-side and generator-side, decouples control of both sides and provides DC-link voltage for Pulse Width Modulation (PWM) modulation.



* DFIG (Doubly Fed Induction Generator)

Electrical protections

When designing a wind power plant it is necessary to provide both control and protection of the different sections of the plant against overcurrent and earth faults.

While wind turbines can be enormous in size, it's the smaller components like ABB's control and protection products that help ensure the availability of electric drive trains, pitch and yaw systems as well as other auxiliary circuits. From breakers to contactors for the electrical drive train, to switches and surge protection devices for the turbine control system, ABB has one of the largest portfolios to ensure reliable and safe operation. Protective devices, such as circuit breakers are required to protect the wind farm and the network from electrical faults.
Careful coordination between contactors and circuit breakers is needed to ensure that all conceivable faults are managed safely, and that no correctly functioning equipment unnecessarily disconnected.

Since wind is a variable and uncertain source, inconsistent and subject to sudden variations, **the dedicated mechanical and electrical devices must guarantee high performance to maximize the extraction of mechanical power and its conversion into electric power for input into the grid.**

For safety reasons in maintenance, emergency and fault conditions, isolation from all possible sources is mandatory. Isolation function cannot be created via contactors, semiconductors, or fuses alone. To fulfill this requirement, a switch-disconnector, a disconnector or a circuit breaker is required.

In addition to the choice of suitable electrical protection, switching and disconnection devices must also be selected and sized carefully.
In particular, from the electrical point of view, this results in frequent operation of the control actuators (e.g., Pitch adjustment or yaw control) and in repeated connection and disconnection of the devices of the power circuit.

Control operations

During normal operation, the stator of doubly-fed drivetrain generators must be disconnected and reconnected due to wind changes several times a day.

This implies heavy stress, in particular for onshore installations subject to wind gusts, where it is quite common to reach 10 to 20 instances a day. In addition, the turbine components, and therefore also the internal electrical components, must operate under heavy environmental conditions, especially in terms of intervals of service temperature.
In huge turbines, the Yaw and the Pitch are particularly important, because improperly positioned nacelle and blades can compromise the structural safety of the turbine. Therefore, there is a Yaw Backup System or a storage system in the pitch.

This is why electrical equipment used for wind applications must be selected with care, considering environmental elements as well thermal and mechanical stresses.

In standby mode for the rotor circuit, to avoid stress in the converter components and lower losses via lower DC-link voltage, the disconnection of the converter supply is recommended. The number of operations is lower than for the stator circuit, but in any case, it can affect the converter components lifespan and reliability. If the rotor circuit converter is connected to the same supply point as the stator, the conditions are the same, as well as the contribution from the generator.

The high number of connect/disconnect operations related to the stator and rotor circuit makes contactors suitable for this purpose. Other products will either introduce high losses (semiconductors) or have a limited mechanical lifespan (ACBs or MCCBs). Contactors are capable of managing the load/generator currents and withstanding the transitory currents.

The function of a contactor is remote switching of the main circuits under normal operating conditions. A contactor is a device designed for many switching cycles, and therefore it is complementary to breakers.

The requirements and sizing of a contactor also depend on whether the switching is carried out with or without a load. When switching with a load, the electrical lifespan of the contactor can be one of the sizing factors; when switching without a load, the mechanical lifespan can be applied.

The contactor, positioned on the stator circuit, is intended for switching operations at higher power (at rated current or in absence of current) and consequently has a larger size.

Short circuit current protection

In large power grids or turbine parks the short circuit level can be up to 25 times the circuit rated current.

Though the high short circuit current values require a protection device able to cut them off, this protection device must protect not only the generator but also the connection elements, as well as the contactor.

For short circuit current protection, a circuit breaker is generally used as a protection device. If it operates too rapidly, it can interfere with the transients with frequent unwanted tripping (and the reset is generally as simple in some locations, like the nacelle of a wind turbine), and the LVRT (Low Voltage Ride Through) requirements cannot be fulfilled.

If it operates in fault conditions, the contactor may not work properly, or if its setting is too high (higher than the minimum short circuit current value, so the contactor is not protected), the contactor is seriously damaged, and it must be replaced. If the correct short circuit protection has not been properly coordinated it could cause damage in the entire installation and possibly fire.

The circuit-breakers must be coordinated with the contactors for switching operations.

Selecting and coordinating protection and control devices

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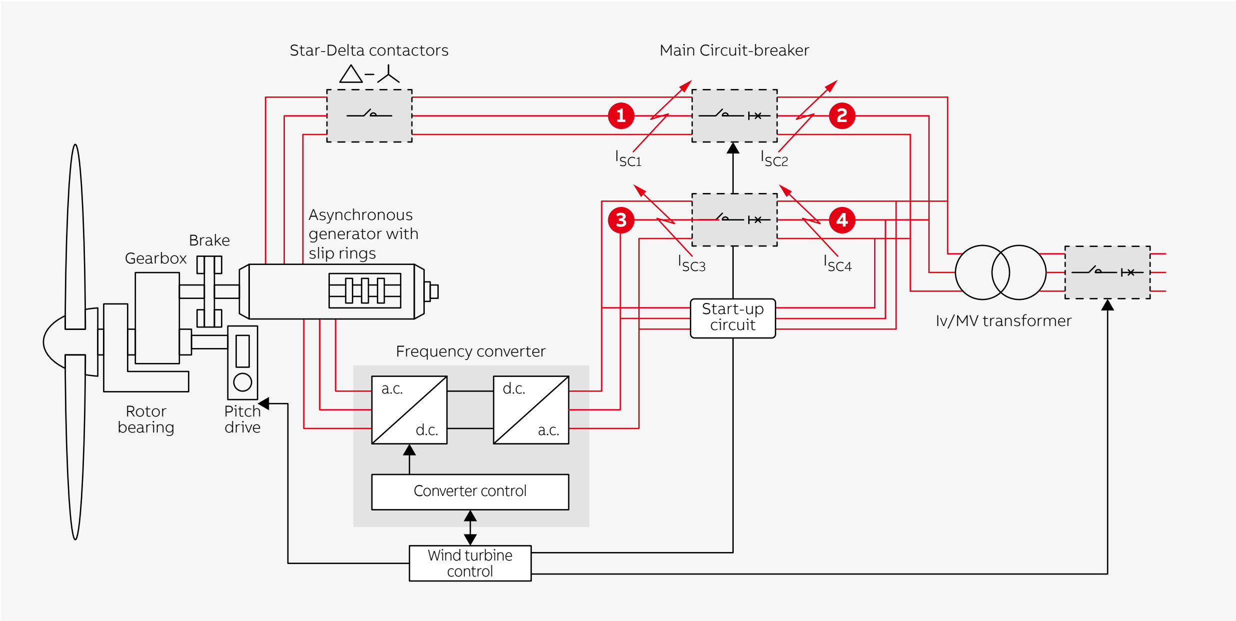
The stator and rotor of the main power circuit of doubly-fed wind generators



The turbine control system acts by commanding the rotor and stator contactors and circuit-breakers, the converter on the rotor, the MV circuit breaker and the pitching system.

There is also the possibility of star-delta connecting the stator windings of the generator by means of contactors properly sized to handle different wind conditions. With regard to selecting the circuit-breaker/contactor coordination, it is possible to refer to the “motor starting/ protection” tables issued by ABB.

At starting, the closing of the start-up circuit on the rotor circuit in parallel with the circuit-breaker/contactor is the first step.
The start-up circuit includes resistance value suitable to limit the start-up current.

Then, the contactor on the main excitation circuit of the rotor is closed, followed by closing of the contactor on the main power circuit of the stator. In this case, the magnetic field inside the generator is caused by the rotor supply. This means that when the supply circuit of the stator is closed there is no inrush current (operating in AC-1).

When starting has been carried out, the start-up circuit is disconnected and therefore, under steady state conditions, the power flowing in the rotor circuit passes through the main auxiliary contactor.

To select the breaking capacity of the LV circuit-breaker positioned on the main power circuit, it is necessary to assess the short circuit currents under different fault conditions:

- **in case of short circuit at point 1**, the fault current Isc1 in the circuit-breaker has a value that depends on the short circuit power of the grid that the wind turbine is connected to, and on the short circuit impedance of the lv/MV transformer. The rotor contribution is added to this value; this contribution is limited to approximately double the rated current of the converter due to the effect of the converter itself;
- **in case of short circuit at point 2**, the fault current Isc2 in the circuit-breaker has an exponential smoothing trend and will be supplied for a limited time by the asynchronous generator due to the effect of the kinetic energy stored in the rotor.

Analogously, with regard to the choice of the breaking capacity of the LV circuit-breaker positioned on the main excitation circuit of the rotor, it is necessary to consider the short circuit currents measured by this circuit-breaker according to the position of the fault:

- **in case of short circuit at point 3**, the fault current Isc3 in the circuit-breaker has a value equal to the sum of the contribution of the grid and of Isc2;
- **in case of short circuit at point 4**, the fault current Isc4 in the circuit-breaker is limited to approximately the double of the rated current of the converter.

To protect the cables on the generator side and on the network side with current carrying capacity Iz in compliance with the Standard IEC 60364, the rated current of the protection device (or, for the adjustable trip units, the current setting for thermal protection) must satisfy following formula:

$I_b \leq I_n \leq I_z$

In addition, for each short circuit current value likely to occur up to maximum values, the specific let-through energy of the circuit-breaker is carried by the connection cables according to the formula:

$(I^2t) \leq K^2\ S^2$

where:

- (I^2t) is the Joule integral, or the energy let through by the circuit-breaker during short circuit (A^2s);
- K is a constant characteristic of the cable depending on the type of conductor and insulating material;
- S is the cross-sectional area of the cable (mm^2).

This formula must be verified for the entire length of the cables. However, given the particular trend of the curve of the let-through energy of a circuit-breaker, it is generally sufficient to verify the formula only for the maximum and minimum value of the short circuit current, which can affect the wiring system.

The maximum value is usually the value of the three-phase short circuit current at the beginning of line, while the minimum value is the value of the short circuit current line-to-line (neutral conductor not distributed) or line-to-earth at the end of the conductor.

Verification of the circuit breaker's performance cannot be simplified by comparing only the specific energy value allowed through the breaker at maximum short circuit current with the energy that the cable can withstand. Additionally, causing the device to trip instantaneously at the minimum short circuit current is not sufficient for verification. In practice, this means that the tripping threshold of the protection against short circuit (taking tolerances into account) must be lower than the minimum short circuit current at the end of line.

In addition, if the cables have current carrying capacity Iz higher than the fault current let through by the converter, the cable protection should be verified only with regard to the constant contribution to the grid.

The circuit-breakers positioned on the main power circuit and on the main excitation circuit isolate the generator stator and rotor converter from the grid.

Therefore, it is necessary to verify that the circuit-breaker guarantees disconnection at the required voltage.

Generally, it is not necessary to install an automatic protection device in the connecting section between the converter and the rotor of the doubly-fed generator. In the case of a short circuit (unlikely, if the connections are state of the art), the generator would operate as if it had a squirrel-cage rotor.
The converter would limit its contribution to the short circuit to a value twice its rated current and would switch to standby mode due to the internal protections.

Selecting and coordinating protection and control devices

The following table summarizes the typical characteristics and requirements to considered when selecting the circuit-breakers and contactors for the main power circuit, for the main excitation circuit and for the start-up circuit.

Data	Value	Value	Value
Type of circuit	main circuit	converter circuit	start up circuit
Load current [A]	≤ 7200	≤ 2000	≤ 20
Voltage [V] and tolerance [%]	≤ 1200 +/-10%	≤ 1200 +/-10%	≤ 1200 +/-10%
Frequency [Hz]	50 / 60 (16.66 on prj)	50 / 60 (16.66 on prj)	50 / 60 (16.66 on prj)
Prospective short circuit current [kA]	≤ 100@1000V /85 (100) kA@ 1200V	≤ 100@1000V /85 (100) kA@ 1200V	≤ 100@1000V /85 (100) kA@ 1200V
Type of load	AC1	AC3	AC3
Presence of inrush current	no	No	yes
Life time [y]	≤ 30	≤ 30	≤ 30
Number of mechanical operations or electrical operations at low current to isolate the system (maintenance or out of service)	100..1000	100..1000	100..1000
Number of mechanical operation or electrical operations at low current to connect or disconnect the generator the the network (production control)	10000..150000	1000..10000	1000..10000
Type of electrical operation full power	emergency stop or protection trip	emergency stop or protection trip	insertion & protection trip
Number of electrical operations	<100 (design: 2000 with different load conditions)	<100 (design: 2000 with different load conditions)	>10000
Protection against overload and short circuit	yes	yes	yes
Allowed fuses on main circuits	no	Yes but obtorto collo	yes
Preferred solutions	Circuit breaker + contactor	Circuit breaker + contactor	Circuit breaker + contactor

Most component data provided in the catalogues only consider behavior of the single standing components “alone”: There is no way to verify if a given product combination selection is protected correctly, based on catalogue data.
It can be tempting to oversize the contactor.

Safety and protection are key values that ABB can provide its customers.

ABB offers a wide range of coordination solutions for protecting and switching, which underline the need for continuous improvement of our customers' installations.

Designers, consultants, OEM, panel builders and end-users must:

- **select the appropriate and optimized selectivity** and back-up coordination between short circuit protection devices
- **provide protection and safety**, further driving down the total cost of ownership
- **reduce the time for selection** and design of your solution

Standard 60947-4-1 defines two distinct types of coordination between breaker and contactor:

- **Type 1** guarantees, in short circuit conditions, that the contactor does not endanger persons or installations but may require maintenance and repair before restarting;
- **Type 2** guarantees, in short circuit conditions, that the contactor does not endanger persons or installations and can operate afterwards. Light welding of contacts may occur and inspection of the installation should be done after a short circuit event.

Performance testing by ABB concluded that use of breakers and contactors from different manufacturers or brands will put customer systems at risk in case of short circuit.
Customer specific testing is necessary to satisfy requests not covered in the coordination table.

Contactors and circuit breakers coordination

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Discover more

Circuit breakers
Circuit-breakers are used to protect the supply circuits of the slip-ring induction generator stator and rotor. The circuit-breakers are coordinated with the contactors for switching operations. In particular, for protection against overcurrent in the electrical devices, such as generators, cables and transformers, it is possible to use Emax series air circuit-breakers and Tmax T series and SACE Tmax XT molded-case circuit-breakers.
Molded-case and air switch-disconnectors can be used to disconnect the generator for maintenance. During maintenance, it is necessary for the EHS (Environment Health and Safety) team to ensure that there is no downstream risk, combining LOTO (Lockout/Tagout) and circuit breakers. Special versions are being developed for operating temperatures from -40°C to +70°.
The circuit-breakers typically used comply with Standards IEC, UL and CCC and are available with the following ratings:
- rated current up to 6300A
- rated voltage up to 1150V
- breaking capacity up to 100kA

For wind installations with limited power, it is possible to use the System Pro M Compact series miniature circuit-breakers.
The nominal characteristics of the Short-Circuit Protective Device (SCPD) must be suitable for any given rated current and voltage, as well as for the corresponding utilization category.

For protection against overcurrent in electrical devices, such as generators, cables and transformer, it is possible to use Emax 2 series air circuit- breakers of the Emax 2 series and Tmax XT series molded-case circuit-breakers.
A wide range of built-in protections are available: overload, short circuit, ground fault, over/under frequency, over/under voltage, reverse power.

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SACE Emax

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Tmax XT

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Discover more

Contactors

The contactors are available for currents up to 2850A.
A special version of contactors AF...T can be used to fulfill the LVRT (Low-Voltage Ride Through) without additional UPS backup. These types of contactors, such as AF1350T – AF2850T, offer time delay built-in together with an electronically controlled coil.

Electrical coordination of contactors and circuit breakers improves system availability and reliability and minimizes damage in components in case of short circuit.
ABB offers a complete coordination table of contactors with MCBs and MCCBs Type 1 and Type 2 coordination, according to IEC 60947 and specific testing as required.

For switching operations, it is possible to use AF contactors coordinated with the circuit-breakers for circuit protection.

These contactors can be used also in the supply circuit in the presence of softstarters or in star-delta connections, to reduce the inrush current.
The wide product range (from AF09 to AF2850) allows switching of load currents up to 2050A in AC-1. In particular, the contactors AF1250, AF2050, AF2650 and AF2850 are designed to be used in applications like wind power systems.

The features include:
- compactness: AF1250 is the most compact 1260A (AC-1) contactor on the market, with the same overall dimensions of AF580 and AF750 contactors; AF2850 has the same dimensions as AF1650 but with higher current (AC-1 rating)
- electronically controlled coil and wide voltage range
- wide range of accessories: all accessories can be used for AF580, AF750, AF1250, AF1350, AF1650, AF2050, AF2650 and AF2850 contactors.

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AF2850T

Contactors and circuit breakers coordination

The rated conditioned short circuit current of contactors protected by a short circuit protective device (SCPD or MPSD) must be verified through the short circuit tests specified in standard IEC 60947-4-1:

a) at the appropriate prospective short circuit current value (test current "r"), and
b) at the rated conditioned short circuit current Iq, if greater than the test current "r".

The use of a short circuit protective devices that do not comply with the manufacturer's specifications may invalidate coordination. Coordination at the tripping current between the contactor and the associated short circuit protective device is a special test.

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Coordinated solution for the main drivetrain circuit

- Electrical coordination of contactors and circuit breakers improves system availability and reliability and minimizes damage in components in case of short circuit.
- We offer complete coordination tables for contactors with ACBs and MCCBs. Type 1 and Type 2 coordination according to IEC 60947.

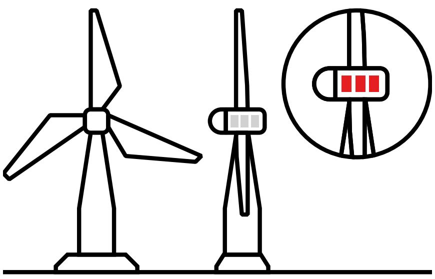

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ABB coordinated solutions tested with breakers and contactors

Contactor	SCPD	Valid coordination
AF1250	Emax2 - E2.2N or E2.2B	690V, 30kA, Type 1
AF1250	Emax2 - E2.2H/E	1000V, 30kA, Type 1
AF1250	Emax - E3H/E2500	1000V, 30kA, Type 1
AF1350	Emax2 - E2.2N, E2.2B or E4.2N	690V, 50kA, Type 1
AF1350	Emax2 - E2.2N, E2.2B or E4.2N	690V, 35kA, Type 2
AF1350	Emax -E3H/E	1000V, 30kA, Type 2
AF1350	Emax2 - E2.2H/E or E4.2H/E	1000V, 30kA, Type 2
AF1350	Tmax T - T7V	690V, 50kA, Type 2
AF1350	Tmax T - T7X	690V, 75kA, Type 2
AF1350	Emax -E3H/E2500	690V, 42kA, Type 2
AF1350	Emax -E2N/E20	690V, 42kA, Type 2
AF1350	Emax -E2N/E2500	690V, 50kA, Type 2
AF1650	Emax2 - E2.2N, E2.2B or E4.2N	690V, 50kA, Type 1
AF1650	Emax2 - E2.2N, E2.2B or E4.2N	690V, 35kA, Type 2
AF1650	Emax2 - E2.2H/E or E4.2H/E	1000V, 30kA, Type 2
AF2050	Emax2 - E2.2N, E2.2B or E4.2N	690V, 50kA, Type 1
AF2050	Emax2 - E2.2N, E2.2B or E4.2N	690V, 35kA, Type 2
AF2050	Emax2 - E2.2H/E or E4.2H/E	1000V, 30kA, Type 2
AF2050	Emax2 - E4.2H/E9 4000 EKIP DPI LSIG	897V, 35kA, Type 2
AF2050	Emax2 - E4.2 H4000/9 EKIP TOUCH LSIG incl 4K-unit	932V, 40kA, Type 2
AF2050	Emax2 - E6.2 H5000/9 EKIP TOUCH LSIG incl 4K-unit	828V, 72kA, Type 2
AF2050	Emax -E3H/E2500	1000V, 30kA, Type 1
AF2050	Emax -E3H/E2500	690V, 35kA, Type 2
AF2050	Emax -E3H/E2500	690V, 50kA, Type 1
AF2050	Emax2 - E4.2H 3200 Ekip Dip LSI 3p WMP, I3= 6	760V, 40kA, Type 2
AF2050	Emax2 - E4.2H 3200 Ekip Dip LSI 3p WMP, I3 = 6 + TVOA arc guard	828V, 40kA, Type 2
AF2050	Emax2 - E4.2N.3200, setting x2	690V, 42kA, Type 2
AF2650	Emax2 - E2.2N, E2.2B or E4.2N	690V, 35kA, Type 2
AF2650	Emax2 - E4.2N.3200, setting x1.5	690V, 42kA, Type 2
AF2650	Emax2 - E2.2N, E2.2B or E4.2N	690V, 50kA, Type 2
AF2650	Emax2 - E2.2H/E or E4.2H/E	1000V, 30kA, Type 2
AF2650	Emax2 - E3H/E3200	1000V, 30kA, Type 2
AF2650	Emax2 - E4.2 H4000/9 EKIP TOUCH LSIG incl 4K-unit	932V, 40kA, Type 2
AF2650	Emax2 - E6.2 H5000/9 EKIP TOUCH LSIG incl 4K-unit	828V, 72kA, Type 2
AF2650	Emax2 - E4.2 H4000/9 EKIP TOUCH LSIG incl 4K-unit	759V, 67kA, Type 2
AF2650	Emax2 - E6.2S6300 EKIP DIP LSIG	759V, 58kA, Type 2
AF2650	Emax2 - E6.2H/E9 6300 Ekip Touch LSI	565V, 86kA, Type 2
AF2650	Emax2 - E6.2H/E9 6300 Ekip Touch LSI 3p	773V, 75kA, Type 2
AF2650	Emax2 - E6.2H/E9 6300 Ekip Touch LSI 3p	857V, 85kA, Type 2
AF2650	Emax2 - E2.2H Ekip Touch LSIG	1050V, 40kA, Type 2
AF2650	Emax2 - E2.2H/E10 MS 2500A	1050V, 40kA, Type 1
AF2650	Emax2 - E6.2H/E9FS	987V, 83kA, Type 2

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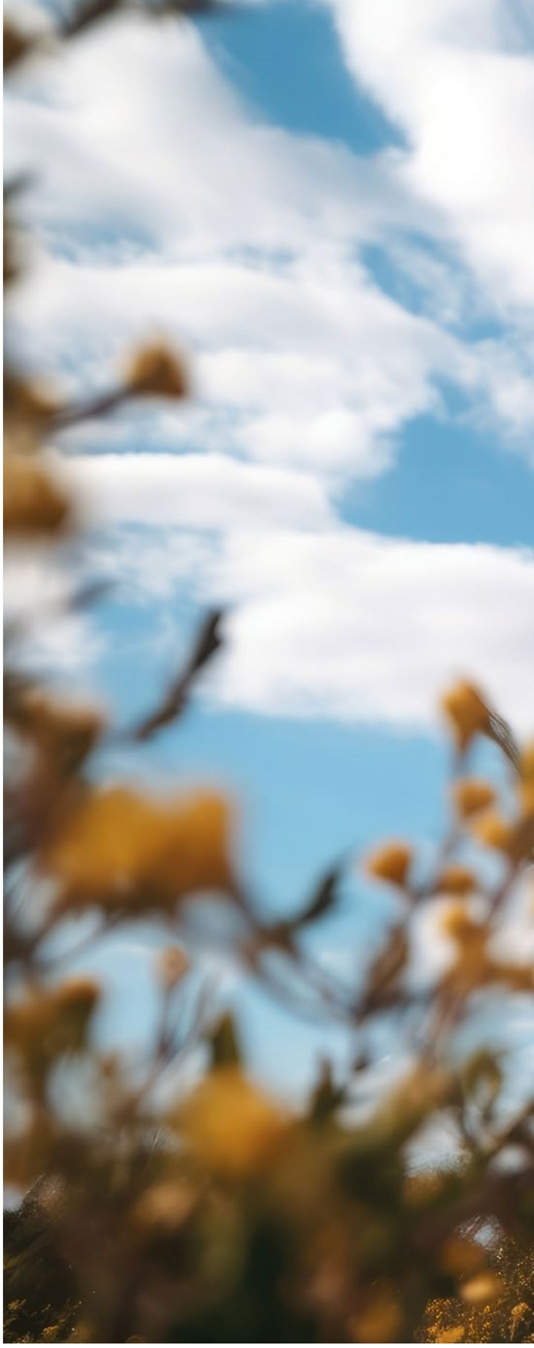

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