Modelling of Alternate Arm Converter in HVDC Applications

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Abstract: *This paper proposes a novel converter topology for HVDC applications; this is known as the Alternate Arm Converter (AAC). The AAC is a half and half topology between the two-level converter and the secluded multilevel converter. Since AAC having H-connect cells as chief switches in each arm of converter. Because of stacking of H-connect cells in AAC it can ready to create a multilevel air conditioning voltage. AAC having capacity to create higher air conditioning voltage than the dc terminal voltage, this permits the AAC to work at an ideal point, called the "sweet spot". At the point when blame happened at dc-side the AAC can directs current in stage reactor through a STATCOM mode operation to help the air conditioner matrix network. The current and voltage qualities at dc and air conditioning side of network are reproduced through MATLAB/SIMULINK.*

Index Terms—*AC–DC power converters, emerging topologies, fault tolerance, HVDC transmission, multilevel converters, power system faults, STATCOM.*

1. Introduction

Presently a day's different new plans are wanted to associate remote sustainable sources to the network. In any case, best approach to do it is to transmit the produced power utilizing HVDC rather than HVAC [1]. For seaward HVDC applications, voltage-source converters (VSCs) are more reasonable than current-source converters (CSCs) [2] because of their dark begin capacity and capacity to work in powerless air conditioning frameworks. Be that as it may, contrasted with CSCs, their power evaluations are constrained and their effectiveness is to some degree poorer. Late advancements in VSCs decrease above disadvantages, some of them [3], [4] to be appointed in the following couple of years. Since the 1990s, a lot of research exertion has been coordinated to enhancing converters principally to make them more power productive than the original of VSCs [5]– [8]. The particular multilevel converter (MMC), distributed in 1998 for STATCOM applications [9], distributed in 2003 for HVDC Power Transmission [10], and followed up in [11]– [13], conveyed a few new highlights to VSC. It supplanted the arrangement associated insulated gate bipolar transistor (IGBT) in each arm of the two-level converter by a heap of half-connect cells which comprise of a charged capacitor and an arrangement of IGBTs. These gadgets brought a few preferences, yet there are a few perspectives that can even now be progressed. The shirking of the air conditioner channel implies that the cells are currently one of the bulkiest segments of the converter station. Half-connect cells are typically utilized as a part of inclination to H-connect cells (both outlined in Fig. 1) keeping in mind the end goal to decrease the quantity of gadgets in conduction whenever and, along these lines, lessen the conduction power misfortune. However, half-connect cells have powerlessness create a negative voltage. It causes to stream of uncontrollable currents in hostile to parallel diodes. Since the dc breakers for high-power applications are still a work in progress [14], [15], the absence of other quick defensive instruments [16] influences this loss of a way to control dc to blame current hazardous. In [17], the double clipped sub module (DCS) was recommended to switch turn around voltage. It is another kind of cell to manage this issue. However the DCS does not completely settle the dc blame issue since: 1) just a large portion of the accessible positive voltage can be converted into negative voltage, leaving a voltage shortage from that expected to completely control the current and 2) the power misfortunes are expanded by 50%compared to utilizing two half-connect cells amid typical operation as a result of the extra IGBT in the conduction way. This paper introduces the examination of another converter topology, which is a piece of another age of VSCs [18], [19], in light of the multilevel approach. This new converter topology gives more points of interest over the all gadgets talked about above. Fundamental preferred standpoint of this new topology lies in its diminished number of cells; along these lines, it doesn't trade off the effectiveness of the converter. A part level reproduction of a 20-MWconverter is utilized to affirm the guaranteed qualities of this new topology.

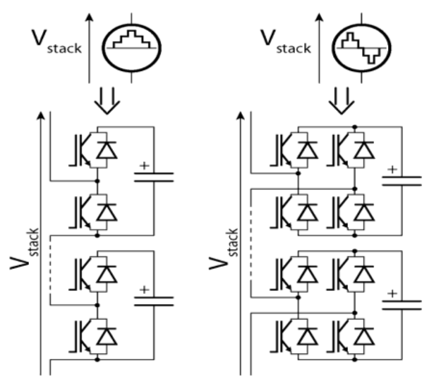
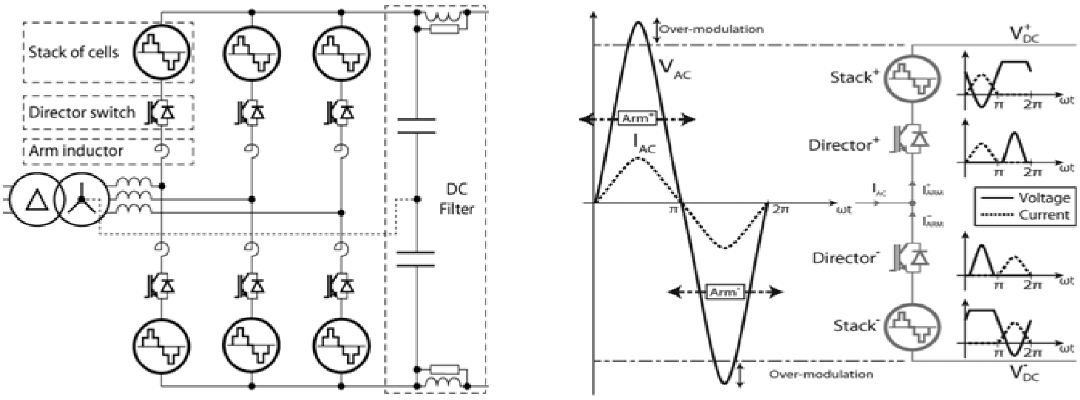


Fig. 1 Electrical schematic of half-bridge cells (left) and H-bridge cells (right).

2. Topology Description

A. Basic Operation

As appeared in Fig.2 (a), each period of the converter comprises of two arms, each with a pile of H-connect cells, an executive switch, and a little arm inductor. The heap of cells is in charge of the multistep voltage age, as in a multilevel converter. Since H-connect cells are utilized, the voltage created by the stack can be either positive or negative.



(a) (b)

Fig. 2 (a) Schematic of the alternate arm converter, with the optional middle-point (b) Idealized voltage and current waveforms over one cycle in a phase converter of the AAC, showing the working period of each arm

The chief switch is made out of IGBTs associated in arrangement keeping in mind the end goal to withstand the most extreme voltage which could be connected over the executive switch when it is in the open state. The primary part of this chief change is to figure out which arm is utilized to lead the air conditioner mutt lease. In reality, the key element of this topology is to utilize basically one arm for every half cycle to deliver the air conditioner voltage. Upper and lower arms are in charge of positive and negative half cycles separately. The subsequent voltage and current waveforms of the cells and reactor switches are outlined in Fig. 2 (b). The brief timeframe when one arm completes its working period and hands over conduction of the stage current to the contrary arm is known as the cover time frame. Preceding opening of chief switch the arm current can be controlled. It causes to decrease of power misfortunes. Notwithstanding this it can likewise control the vitality put away in stack cells.

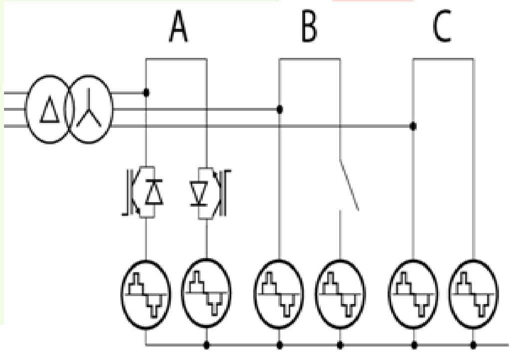


Fig. 3 STATCOM modes of the AAC during a dc-side fault: alternate arms (mode A), single working arm (mode B), and dual working arms (mode C).

B. DC Fault Management

One of the imperative qualities of this converter is the capacity of its arms to create negative voltage. AAC put to use in ordinary operation when the converter creates a voltage which is higher than the dc transport voltage. It can be reached out to the situation when the dc transport voltage falls to a low level, for instance, a blame on the dc side. Since enough cells are available in the stacks to restrict the air conditioner lattice voltage, the converter is in this way ready to monitor the majority of its inside currents, as opposed to the two-level converter or half-connect rendition of the MMC. Moreover, regardless of whether the nonattendance of a dc transport voltage implies that it is never again conceivable to trade dynamic power to the dc side, it doesn't forestall receptive power trade with the air conditioner side. Since the arms of the AAC are as yet operational, the whole converter would now be able to go about as a STATCOM, like that in [9]. Fig. 3 represents operation of executive switch at various modes accomplished by AAC amid a dc-side blame: one arm conducts for every half cycle correspondingly to ordinary operation, one arm works consistently or the two arms cooperating, possibly expanding the receptive power ability to 2.0 p.u. This STATCOM method of dealing with the converter amid dc blame can bolster the air conditioner network amid a dc blackout.

C. Energy Balance

Because of the expansive number of cells, the measure of vitality which is put away by the heaps of cells is more. The main prerequisite left to guarantee attractive operation of the converter is to keep the vitality of the stacks near their ostensible esteem. To accomplish this, the converter must be worked in such way that the net vitality trade for the stacks over every half cycle is entirely zero. In light of the time capacities (1) of $V_{AC}(t)$ and $I_{AC}(t)$

$$V_{AC}(t) = \hat{V}_{AC} \sin \omega t$$

$$I_{AC}(t) = \hat{I}_{AC} \sin(\omega t + \phi_{AC}) \quad (1)$$

The energy exchange corresponds to difference between the amount of energy coming from the ac side (2) and going to the dc side (3)

$$E_{AC} = \int_0^{\frac{T}{2}} V_{AC}(t) I_{AC}(t) dt = \frac{\hat{V}_{AC} \hat{I}_{AC} \cos(\phi_{AC}) T}{4} \quad (2)$$

$$E_{DC} = \int_0^{\frac{T}{2}} \frac{V_{DC}}{2} I_{AC}(t) dt = \frac{V_{DC} \hat{I}_{AC} \cos(\phi_{AC}) T}{2\pi} \quad (3)$$

By equating these two energies, an ideal operating point is obtained as described in (4). This operating point is called the "sweet spot" and is defined by a ratio of the ac voltage magnitude to dc voltage magnitude

$$\hat{V}_{AC} = \frac{2}{\pi} V_{DC} \Leftrightarrow V_{line} = \frac{2}{\pi} \sqrt{\frac{3}{2}} V_{DC} \quad (4)$$

This sweet spot determines an air conditioner crest voltage higher than the dc terminal voltage, that it is a large portion of the dc transport voltage. The converter is in this manner required to create its air conditioning voltage in finished balance mode, at a level of roughly 27% higher than the dc terminal voltage. The nearness of H-connect cells is hence completely defended since these cells are required to give a negative voltage, along these lines pushing the voltage higher than the dc terminal voltage. By picking the turn's proportion of the transformer between the converter and the air conditioner framework keeping in mind the end goal to get the air conditioner voltage of the sweet recognize, the changed over vitality will course through the converter without a shortfall or surplus being traded with the stacks

D. Number of Devices

The gadget check in the AAC can be acquired by following a progression of steps, given the specific working instrument portrayed some time recently. The estimation introduced beneath just gives the insignificant prerequisite under ordinary operation. To start with, the quantity of cells is acquired by ascertaining the most extreme voltage that a stack needs to create. Following are a few cases that diverse voltages are required. For ordinary operation of single-stage converter the greatest voltage would be add up to dc transport voltage, and accepting a symmetrical development, this most extreme voltage must be at any rate a large portion of the dc transport voltage. Besides, given that this topology is proposed to have dc-blame blocking capacity, the arms ought to have the capacity to create at any rate the air conditioner crest voltage that ought to diminish dc voltage to zero. Along these lines, the stacks ought to be evaluated to convey the air conditioner crest voltage. Since the sweet spot characterizes the air conditioner crest voltage as 27% higher than a large portion of the dc transport voltage. In any case, if dc-blame blocking isn't a necessity, this voltage can stay at a large portion of the dc transport voltage. The more extended the cover time frame, the higher the voltage that the stack needs to deliver, subsequently the more cells are required. Second, the required number of arrangement IGBTs, which shape the executive switch, is resolved in light of the most extreme voltage connected over the chief switch, as showed in Fig. 3. This voltage is the distinction between the converter voltage and the voltage at the opposite end of the executive switch, which is associated with the (non-directing) pile of cells. The non-leading stack can be set to boost its voltage keeping in mind the end goal to bring down the voltage over the executive switch, taking consideration not to turn around the voltage over the chief switch. Condition (5) compresses these contentions and presents the most extreme voltage over the chief switch. Once the most extreme voltage of the stack is set, the quantity of cells is straightforwardly acquired by isolating this voltage by the ostensible voltage of a cell. Substituting (4) into (5), it yields (6), an element of the dc transport voltage and the pinnacle stack voltage.

$$\hat{V}_{Director} = \hat{V}_{AC} + \frac{V_{DC}}{2} - \hat{V}_{Stack} \quad (5)$$

$$= \frac{4+\pi}{2\pi} V_{DC} - \hat{V}_{Stack} \quad (6)$$

Table I abridges the voltage appraisals expected of the pile of cells and the chief switch given three decisions made over the need to piece dc blame current and the degree of cover.

TABLE I: VOLTAGE RATINGS OF THE STACKS AND DIRECTOR SWITCHES

$\hat{V}_{Stack}$	$\hat{V}_{Director}$	Remarks
$\frac{V_{DC}}{2}$	$\hat{V}_{AC}$	No DC-fault blocking and no overlap
$\hat{V}_{AC}$	$\frac{V_{DC}}{2}$	DC-fault blocking and short overlap
$\hat{V}_{DC}$	$\hat{V}_{AC} - \frac{V_{DC}}{2}$	DC-fault blocking and full cycle overlap

The resulting number of cells per stack is given by (7), where V_{Cell} is the nominal voltage of a cell

$$N_{Cell} = \frac{V_{Stack}}{V_{Cell}} \quad (7)$$

Condition (8) shows the aggregate number of semiconductor de-indecencies (N_{IGBT})in a three-stage AAC, with $N_{Director}$ being the number arrangement IGBTs in the chief switch acquired by isolating the greatest voltage of an executive switch ($N_{Director}$) by the voltage connected to an IGBT, here thought to be the same to the voltage of a cell (N_{Cell}).

$$N_{IGBT} = 6 \times (4 \times N_{Cell} + N_{Director}) \quad (8)$$

Utilizing the dc-blame blocking case (given in Table I) and the meaning of the sweet spot (4), the aggregate number of semiconductor gadgets turns into the estimation of the following equation:

$$N_{IGBT} = 6\frac{4\hat{V}_{AC}+\frac{V_{DC}}{2}}{V_{Cell}} = 18.28\frac{V_{DC}}{V_{Cell}} \quad (9)$$

This is utilized to locate the quantity of cells in converters at various voltage levels. By substituting distinctive voltages in (9) number IGBTs are fluctuated. In AAC these switches check is diminished than that of all converters. So productivity of AAC is increasingly when contrasted with all converters as talked about some time recently. The reenactment models and aftereffects of AAC converter is clarified as takes after.

3. Simulation Results

A. Model Characteristics

Keeping in mind the end goal to affirm the operation of this new topology, a recreation demonstrate has been acknowledged in Simulink utilizing Sim Power System. Key parameters for reproduction are condensed in Table II. The quantity of cells decided for each stack takes after the second case from Table II so dc-side blame blocking is accessible. A little extra remittance was made so the converter can in any case work and square blames with an air conditioner voltage of 1.05 p.u. The decision is in this way for nine cells charged at 1.5 kV each per stack. The base number of cells for operation without cover (sweet spot operation just) and without blame blocking would be seven cells. The decision of nine cells for each stack permits the AAC to work with 1-ms cover period which is adequate to inside deal with the energy storage inside the dog lease rating of the IGBTs (1.2 kA). At last, a dc channel has been fitted to the AAC demonstrate, as represented in Fig. 2, and tuned to have basic damping and a cutoff recurrence at 50 Hz; well underneath the primary recurrence part expected on the dc side which is a six-beat swell (i.e., 300 Hz in this model).

TABLE II: CHARACTERISTICS OF THE 20-MW AAC MODEL

Characteristics	**Values**
Active power	±20 MW
Reactive power	±5 MVAr
DC bus voltage	20 kV
Grid-side AC voltage	11 kV
Converter-side AC voltage	15.56 kV
Phase reactor	3.9 mH
Arm inductor	0.5 mH
DC Filter inductors (x2)	6 mH
Quality factor of DC inductors at 50 Hz	100 (19 $m\Omega$)
DC Filter capacitors (x2)	1.68 mF
Total energy in DC bus capacitors	168 kJ
DC Filter resistors (x2)	2.66 Ω
Overlap period	1.0 ms
Cell voltage	1.5 kV
Cell capacitor	4.0 mF
Stacks	9 cells
Director switches	7 IGBTs
Converter voltage waveform	**19 levels**
Total number of semiconductor devices	**258 IGBTs**

B. Performance under Normal Conditions

In view of this model, the conduct of the AAC was reproduced under ordinary conditions to test its performance. In this segment, the converter is running in rectifier mode, changing over 20 MW and giving 5-MVAr capacitive receptive power. Fig. 4 demonstrates the waveforms created by the AAC in this recreation. To start with, the converter is extremely responsive. Second, the waveform of the stage current in the air conditioner network association is high caliber with just low abundancy music. Third, the dc current shows the trademark six-beat swell intrinsic in the correction strategy for this converter, however weakened by an inductor set between the converter and the dc matrix. Fourth, this correction activity of the current is especially discernible in the fourth diagram which demonstrates the arm currents in stage A, showing when an arm is directing. At long last, the fifth diagram shows the normal voltage of the cells in the two heaps of stage A, with their OFF state voltage being controlled to remain at the reference estimation of 1.5 kV.

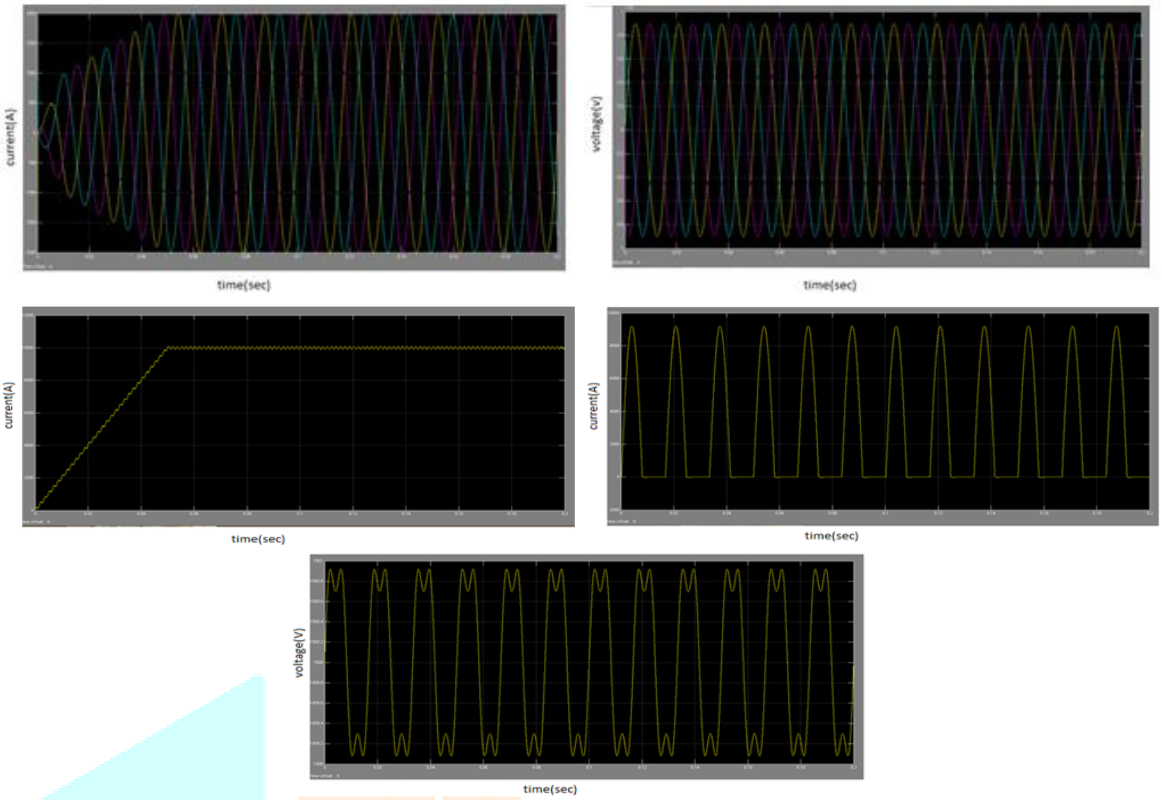


Fig. 4 Simulation results of a 20-MW AAC model running in rectifier mode under ordinary conditions.

The voltage and current waveforms have been post prepared together with the changing summons sent to the converter from the controller, so as to decide the created power misfortunes. For this illustration, the greater part of the semiconductor gadgets depended on the same IGBT gadget [21] from which the misfortunes bends have been extricated to register the energy lost through conduction and exchanging at each reenactment time step (2s). The acquired outcomes are condensed in Table III. As can be seen in Table III, the changing misfortune in respect to the aggregate power misfortunes is low, yet conduction misfortune is similarly more than exchanging misfortunes.

TABLE III: BREAKDOWN OF THE POWER LOSSES AT 20 MW

Stack power losses	Value
Conduction	103 kW
Switching	26 kW
Reverse Recovery	10 kW
Director switch power losses	**Value**
Conduction	36 kW
Switching	0 kW
Reverse Recovery	0 kW
DC-filter power losses	**Value**
Conduction	56 kW
Total Power Losses	**191 kW**
Efficiency	**98.85 %**

C. Robustness against AC Faults

Since the AAC is a kind of VSC, it doesn't depend on a solid air conditioning voltage to work. As a result, the AAC can adapt to air conditioning side shortcomings. Fig. 6 demonstrates the consequences of the recreation where the air conditioner voltage drops to 0.3-p.u. held voltage in the vicinity of 0.20 and 0.35 s, like a noteworthy blame on the air conditioner lattice. A few perceptions can be made. Initially, the converter can respond rapidly to the blame and lessens the power as a result. Second, the nature of the air conditioner current waveform weakens amid the blame, for the most part in light of the fact that less levels are expected to build the decreased converter voltage waveform. Third, the phone capacitors show more prominent voltage change amid the blame in light of the fact that the converter is fleeing from the sweet spot, however this does not keep the AAC from creating receptive power amid the blackout.

D. DC Fault Blocking Capability

To know the dc blame blocking ability of AAC, the dc voltage is kept to zero incidentally. Fig.7 demonstrates the waveforms created amid this reproduction, where the dc transport voltage is lost in the vicinity of 0.20 and 0.35s took after by an increase back to typical operations. While watching the grouping of occasions amid reenactment, it can be seen that when the dc voltage falls to zero, it prompts a quick release of the dc transport capacitor which is outside the control of the converter contrary to the cell capacitors. Right now of blame, the dc channel carries on like a RLC circuit with a pre charged capacitor (20 kV) and inductor(1 kA), bringing about a hypothetical pinnacle current of 5.1 kA which is near the current spike saw in the third chart. Notwithstanding, the fourth chart demonstrates that the converter can keep control of the air conditioner reactor current and its arm currents with the goal that no blame mutt lease streams from the air conditioner side to the dc side, exhibiting the dc blame blocking ability of the converter itself.

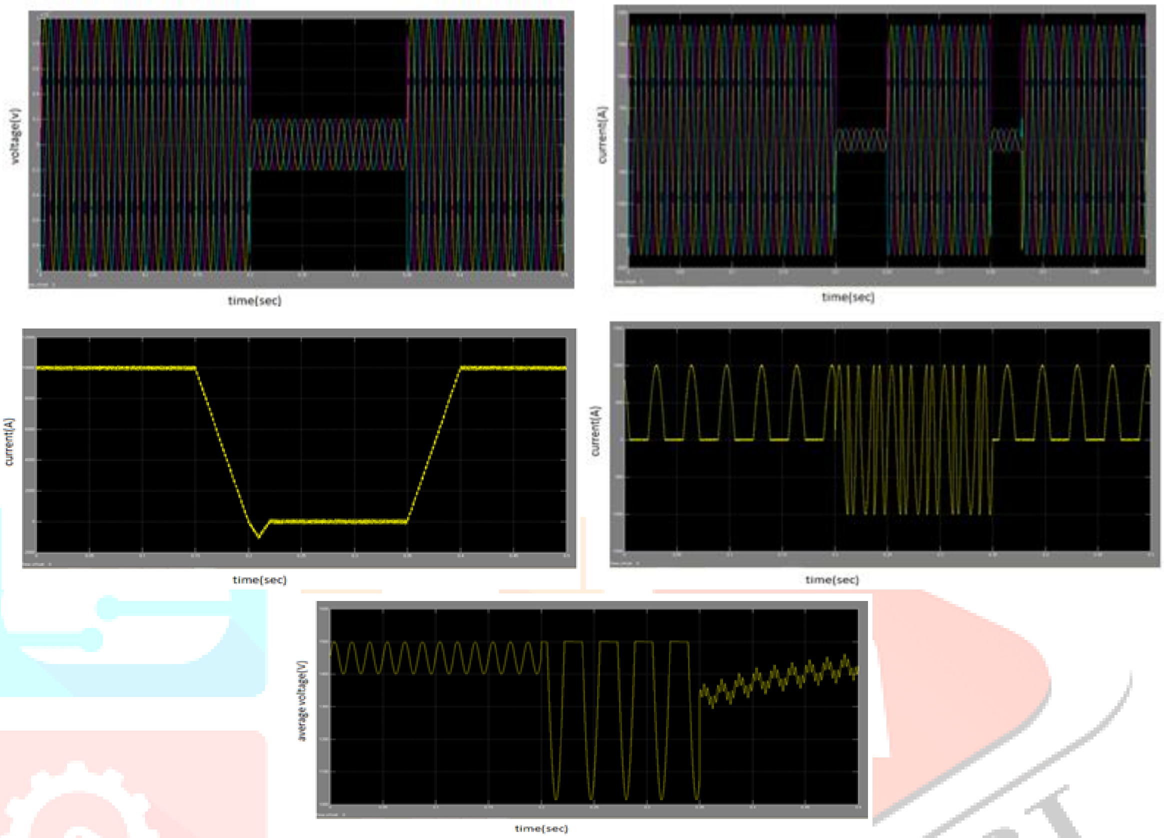
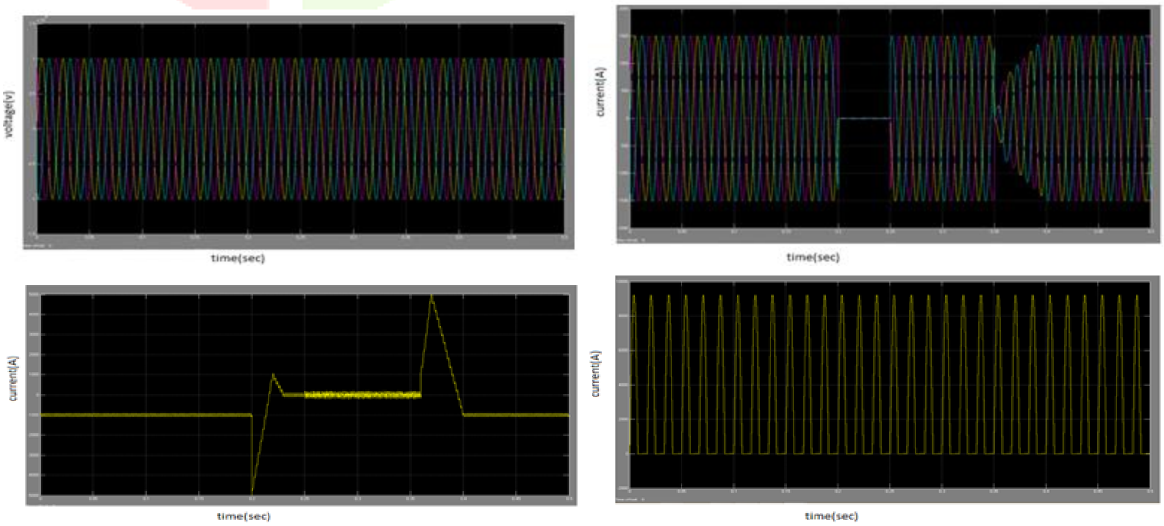


Fig. 5 Simulation results of a 20-MW AAC model running in rectifier mode when an ac-side fault occurs between 0.20 and 0.35 s.

This reproduction demonstrates the capacity of the AAC to adapt to the dc-side blame and even keep running as a STATCOM to help the air conditioner framework, without dc transport voltage. Moreover, in the current reproduction, the AAC keeps the same rotating instruments of its arms (mode A in Fig. 3) be that as it may, by initiating the two arms constantly (mode C in Fig. 3), the most extreme responsive power could reach up to 2.0-p.u. current.



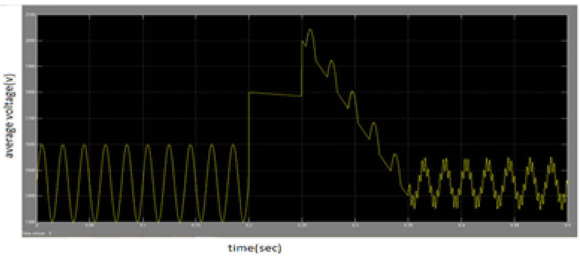


Fig. 6 Simulation results of a 20-MW AAC model running in rectifier mode when a dc-side fault occurs between 0.20 and 0.35 s.

4. Conclusion

AAC produces symphonious free air conditioning current with joining heaps of H-connect cells with executive switches. It can be worked with less number of cells than MMC for a similar operation. It represent the trading of energy between the air conditioner and dc sides of system. In situations where this harmony isn't accomplished, a cover period can be utilized to run a little dc current keeping in mind the end goal to adjust the stacks by sending the overabundance energy back to the dc capacitors. In situations where this harmony isn't accomplished, a cover period can be utilized to run a little dc current so as to adjust the stacks by sending the overabundance energy back to the dc capacitors. A discourse of the aggregate number of gadgets required by this topology has additionally been introduced. Giving dc blame blocking and cover both require more than the absolute minimum number of cells. Reproductions of a little scale display demonstrate that this converter can convey performance under typical conditions, as far as effectiveness and current waveform quality, and give fast reactions on account of air conditioning or dc-side shortcomings. Its capacity to keep control of the current notwithstanding amid dc deficiencies is a huge favorable position, particularly in multi terminal HVDC applications, and can be stretched out into STATCOM operation with a specific end goal to help the air conditioner network amid the blackout, by giving conceivably up to 2.0-p.u. responsive current.

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