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Voltage Source Converter Representation for Efficient and Credible RMS Studies

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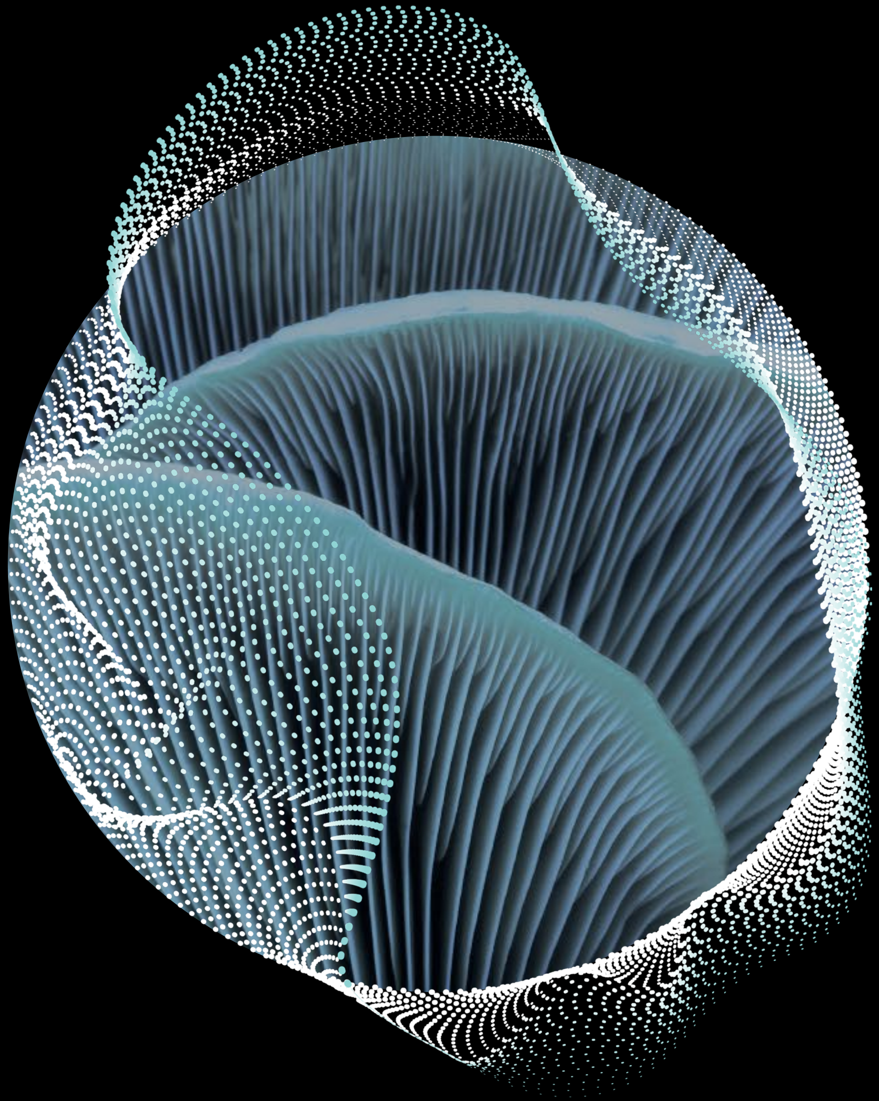

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❑Background

- ✓ RMS simulations play pivotal role in de-risking of project s, from planning to detailed design studies, i.e., identification of risks and mitigations), for examples:
  - Provide preliminary indication if network reinforcements are needed (steady-state and dynamic operation).
  - Fault levels as key inputs for planning and design studies (ratings, bus arrangements, screening of risks of control systems instability and control interactions, etc.).
  - Preliminary assessment of stability (first swing, voltage, frequency, etc.) and of countermeasures.
- ✓ Their fast speeds, make them suitable for batch simulations and design optimization.

Summary

For the RMS simulations to remain relevant during energy transition that largely rely on converter interfaced renewable generations, significant improvements are needed to ensure they produce meaningful results that in fact contribute to de-risking of projects.

❑ Motivations

With increased uses of power electronics in generation, transmission and distribution systems, traditional positive phase sequence voltage source converter (VSC) RMS models exhibit significant limitations, for examples:

- ✓ Unable to reproduce correct behaviors in weak ac networks, $1 \leq SCR \leq 3$.
- ✓ Exaggerate issues, which can lead to over-investments in assets not needed, as their limitations and inaccuracies give false sense of operation near stability limits.

Summary:

Some of the above limitations could be attributed to:

- o Lack of alignments between RMS control structure and the actual structure in the physical VSC as EMT VSC models attempted to implement.
- o Over-interpretation of the results of the RMS simulations beyond its scope.

❑ Proposed VSC model:

To address some of the above limitations of existing VSC models highlighted above:

- ✓ This work presents a VSC RMS model with control structure closely aligned with that of the generic VSC in EMT, outer and inner loops, with both positive and negative phase sequence accounted for.
- ✓ Presents one-to-one validation of the proposed VSC model against EMT equivalent.

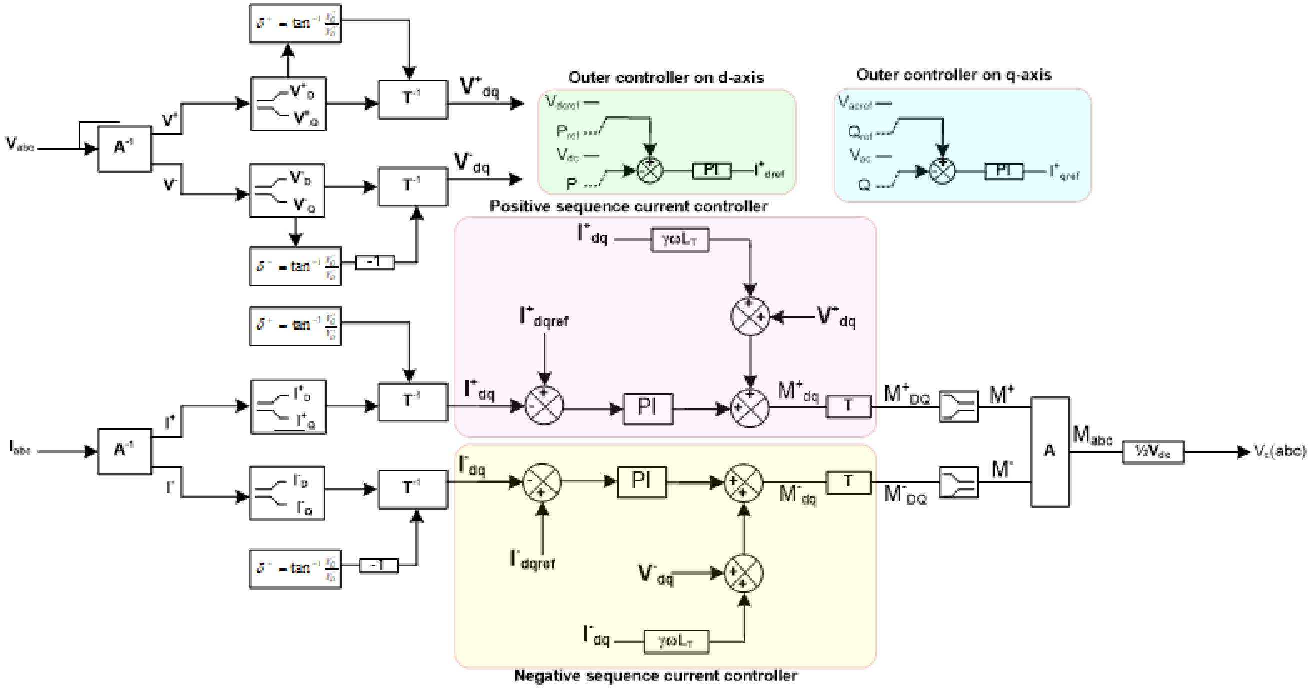


Fig. 2. VSC control system in RMS

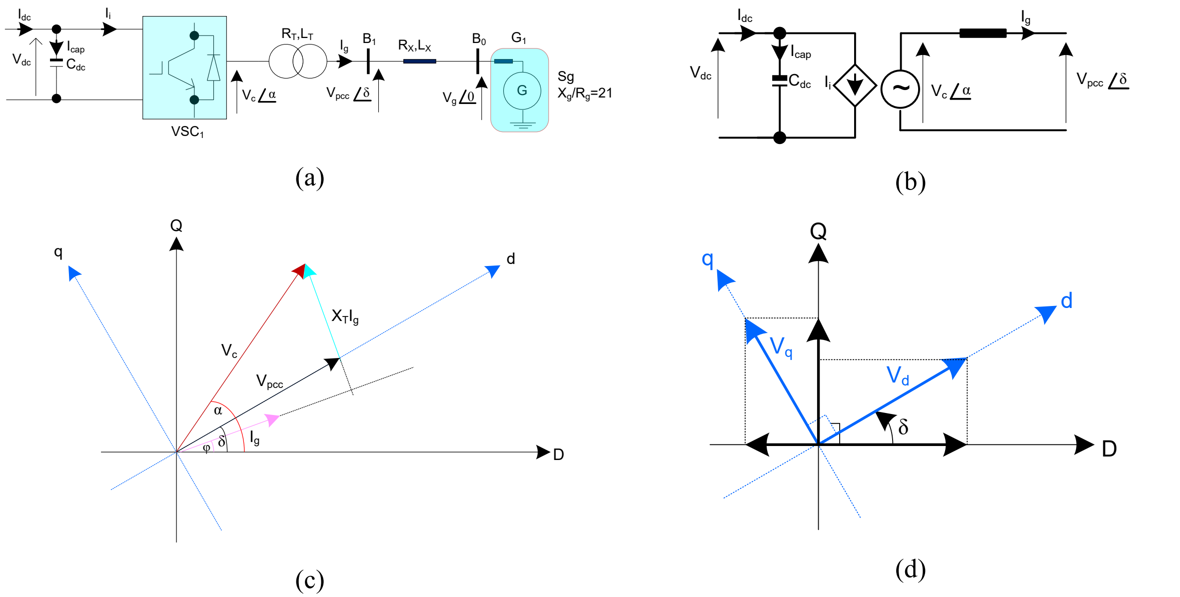


Fig. 1. (a) Schematic diagram of grid connected VSC, (b) Simplified VSC average or RMS model, (c) phasor diagram, and (d) Reference frame unification

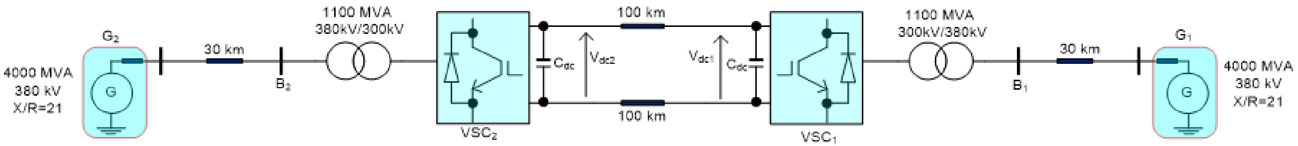


Fig. 4. Illustrative test system for point-to-point HVDC link with 525 kV rail-to-rail dc voltage.

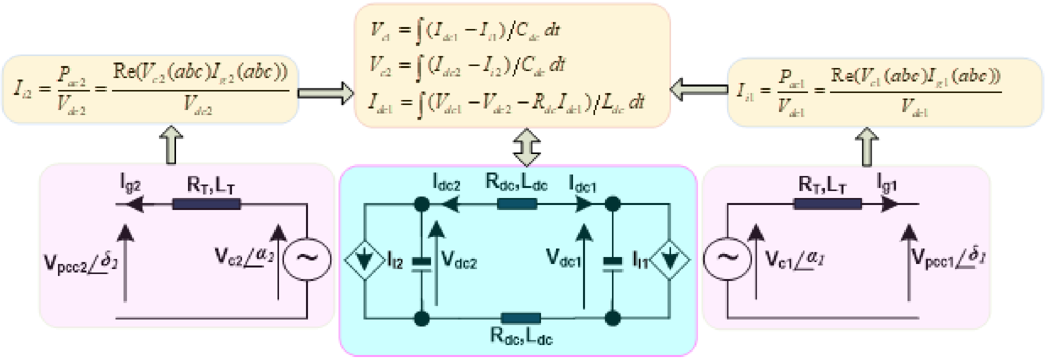


Fig. 3. Summary of VSC based HVDC transmission system implementation in RMS, with sections highlighted in the yellow boxes show dc circuit implementation

$$T^{+} = \begin{bmatrix} cos\delta^{+} & -sin\delta^{+} \\ sin\delta^{+} & cos\delta^{+} \end{bmatrix}$$

$$\begin{bmatrix} V_D^{+} \\ V_Q^{+} \end{bmatrix} = \begin{bmatrix} cos\delta^{+} & -sin\delta^{+} \\ sin\delta^{+} & cos\delta^{+} \end{bmatrix} \begin{bmatrix} V_d^{+} \\ V_q^{+} \end{bmatrix}$$

$$A = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix}$$

$$T^{-} = \begin{bmatrix} cos\delta^{-} & sin\delta^{-} \\ -sin\delta^{-} & cos\delta^{-} \end{bmatrix}$$

$$\begin{bmatrix} V_D^{-} \\ V_Q^{-} \end{bmatrix} = \begin{bmatrix} cos\delta^{-} & sin\delta^{-} \\ -sin\delta^{-} & cos\delta^{-} \end{bmatrix} \begin{bmatrix} V_d^{-} \\ V_q^{-} \end{bmatrix}$$

$$\gamma = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

❑ Observations:

- ✓ Accurate reproduction of the dc side dynamics requires small time-step of 50μs to 200μs, which is counterproductive as it slows down the overall simulation and renders the model inadequate for use in large ac networks.
- ✓ If dc line/cable inductance is ignored, large time-step of 100μs to 1000μs can be used to substantially improve simulation speeds, without impacting the accuracy of the ac side dynamics.
- ✓ When the proposed VSC RMS is used with adequate simulation time-step, it can extend the scope of RMS simulation to include fast fault current injections (FFCI) during symmetrical and asymmetrical ac faults, which are not possible using existing positive sequence VSC RMS models.

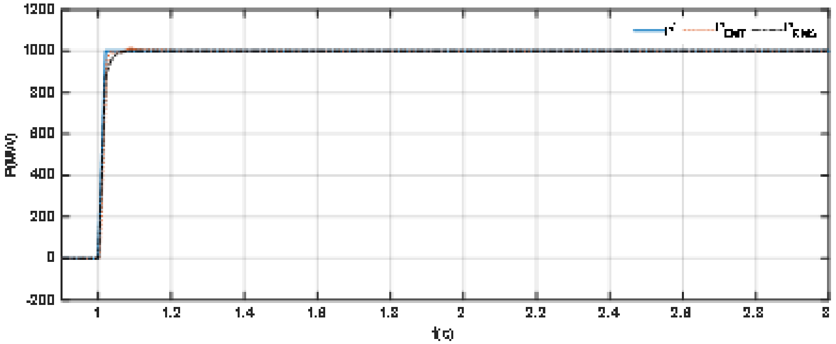
❑ Simulations:

In ±262.5 kV symmetrical monopole P2P HVDC link in Fig.5, each converter is rated for 1000 MW and ±480 Mvar:

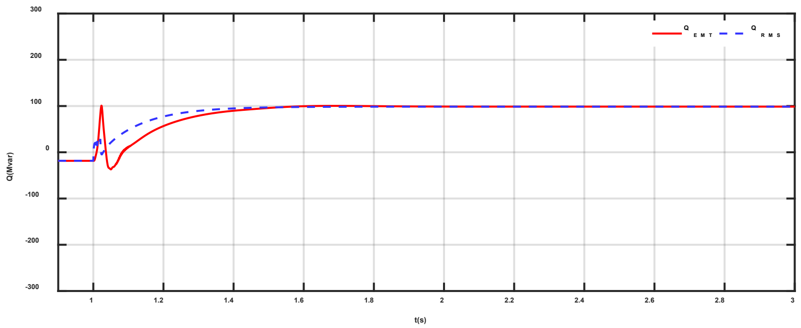
- ✓ VSC_1 controls dc voltage (V_{dc1}) and ac voltage (V_{ac1}) or reactive power (Q_1).
- ✓ VSC_2 controls active power (P_1) and ac voltage (V_{ac2}) or reactive power (Q_2).
- ✓ Negative sequence is controlled at zero.

One-to-One Validation of the proposed VSC RMS Model Against EMT Equivalent

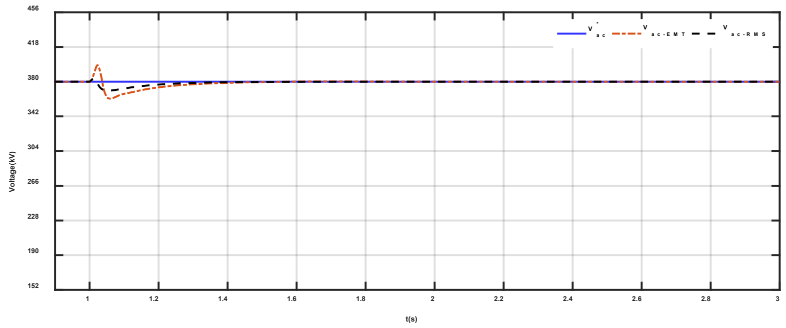
❑Active Power Step Change



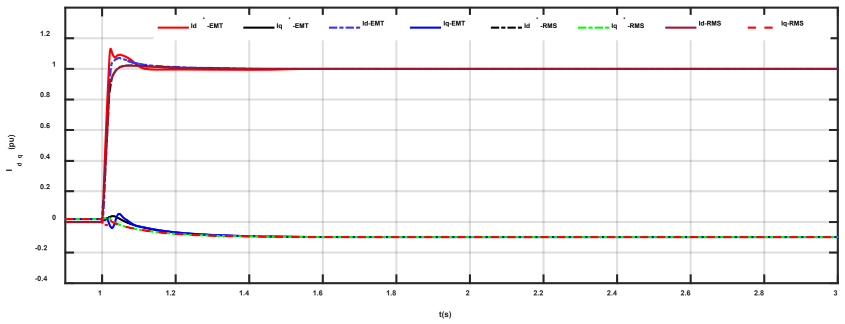
VSC2 active power at B2



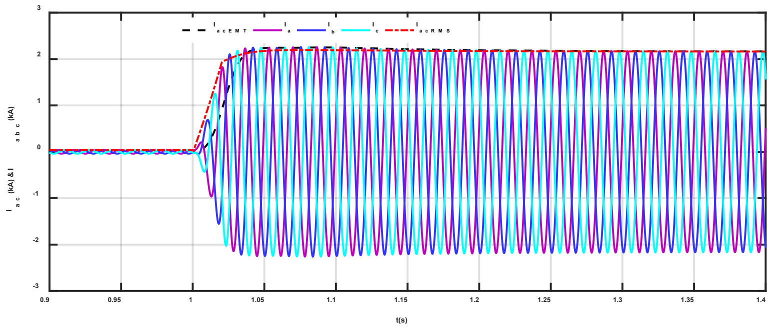
VSC2 reactive power at B2



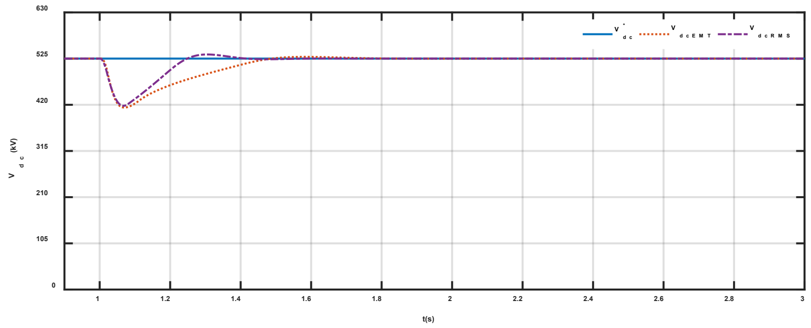
VSC2 magnitudes of the line-to-line ac voltage at B2



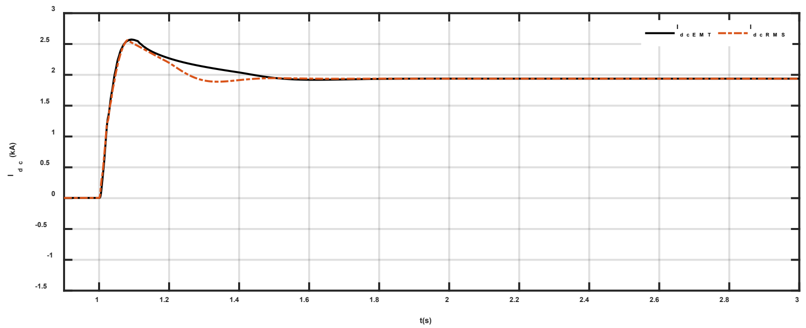
VSC2 per d-q currents



VSC2 three-phase instantaneous currents superimposed on the peak current magnitude



VSC1 dc voltage



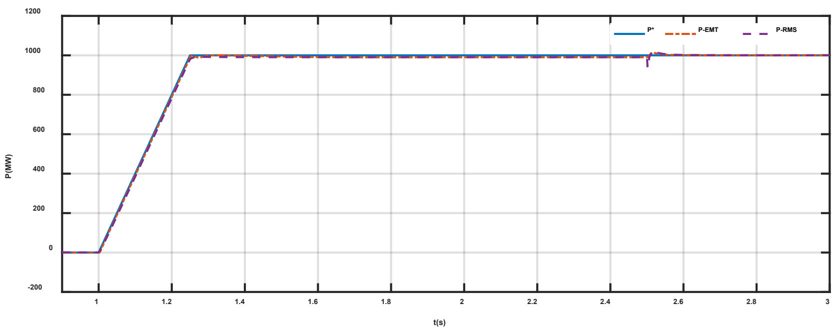
dc current

Fig. 5. One-to-one comparison of selected EMT and RMS simulation waveforms when step change is applied to the active power order of VSC_2

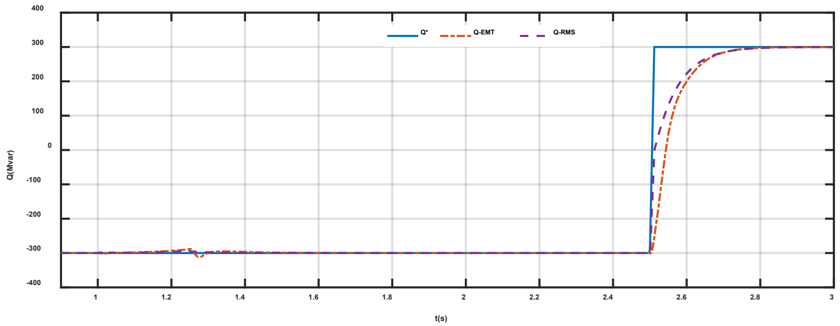
Summary:

- ✓ At t=1s, VSC_2 steps its active power from 0 to 1000 MW at B_2 while it regulates ac voltage at B_2 at 380 kV.
- ✓ Observe the RMS and EMT equivalent waveforms are closely matched.

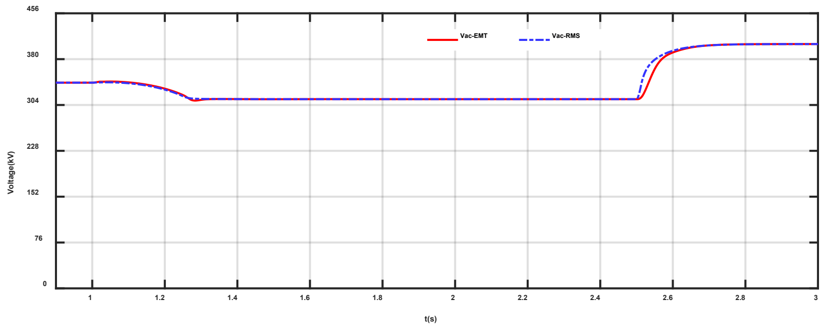
❑Reactive Power Step Change



VSC2 active power at B2

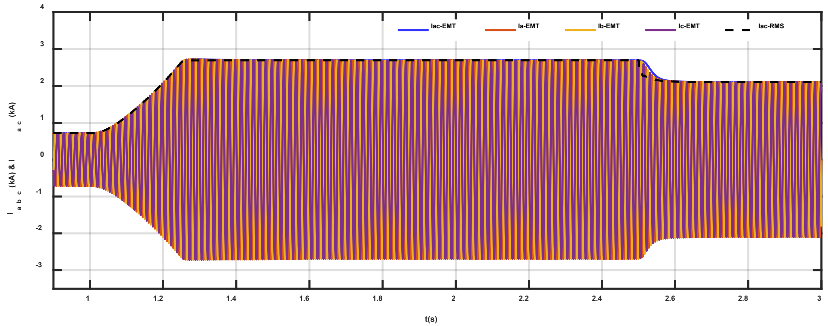


VSC2 reactive power at B2



VSC2 magnitudes of the line-to-line ac voltage at B2

Fig. 6. One-to-one comparison of selected EMT and RMS simulation waveforms when step change is applied to reactive power order of VSC_2



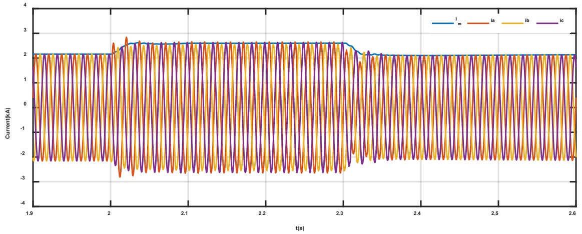
VSC2 three-phase instantaneous currents superimposed on the peak current magnitude

Summary:

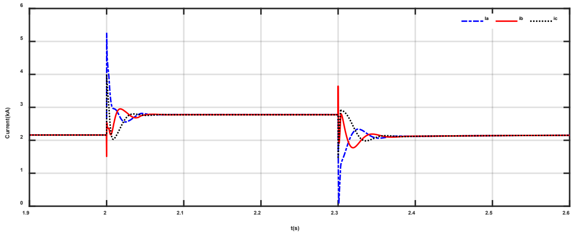
- ✓ At t=2.5 s, VSC_2 steps its reactive power from -300 Mvar to +300 Mvar at B_2 while it regulates its active power exchange with B_2 at 1000 MW.
- ✓ Observe the RMS and EMT equivalent waveforms are closely matched.

❑Single-phase to ground ac fault

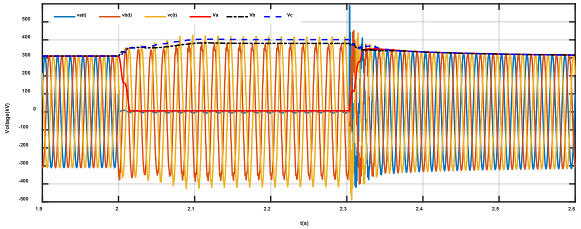
EMT	RMS



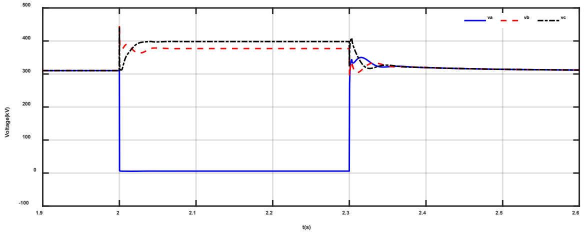
(a) three-phase instantaneous ac currents and its magnitude



(b) Magnitudes of three-phase ac currents

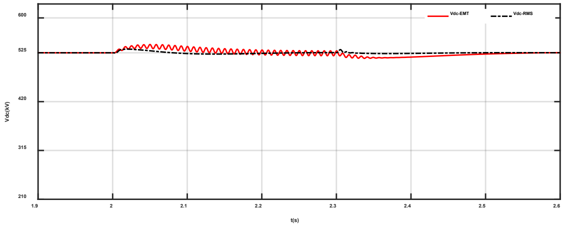


(c) Three-phase ac voltages and their magnitudes

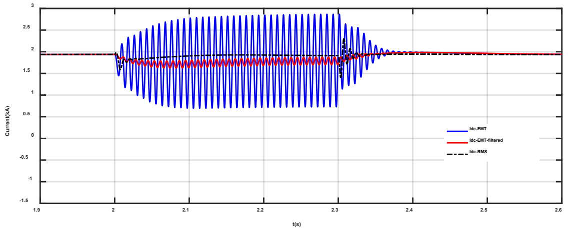


(d) Magnitudes of three-phase ac voltages

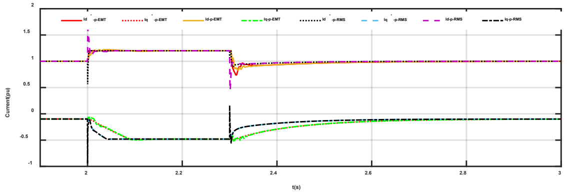
RMS superimpose over EMT



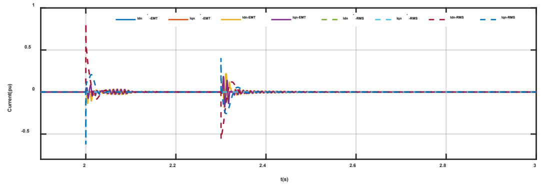
(a) dc voltage



(b) dc current



(c) positive sequence d-q currents



(d) negative sequence d-q currents

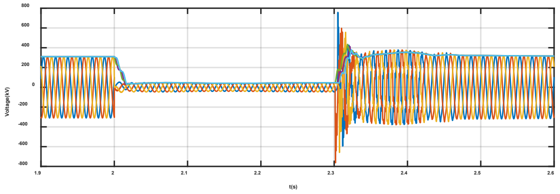
Fig. 7. One-to-one comparison of selected EMT and RMS simulation waveforms when VSC2 is subjected to 300 ms single-phase-to-ground ac fault

Summary:

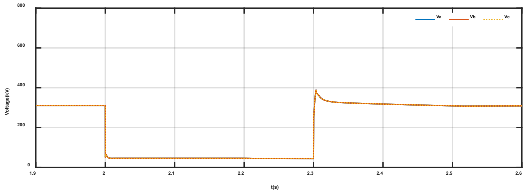
- ✓ In pre-fault t<2 s, VSC_2 injects 1000 MW into B_2 and regulates ac voltage at B2 at 380 kV.
- ✓ At t=2 s, B2 is subjected to 300 ms single-phase ac fault.
- ✓ Observe the RMS and EMT equivalent waveforms are closely matched, including three-phase currents and voltages as negative phase sequence suppressed to zero, and dc side dynamics.

❑Three-phase to ground ac fault

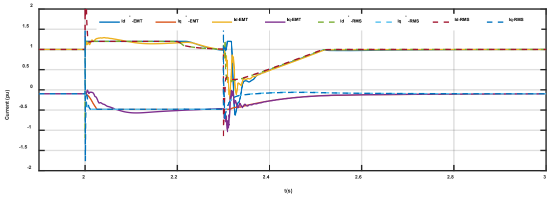
EMT	RMS	EMT superimposed on RMS



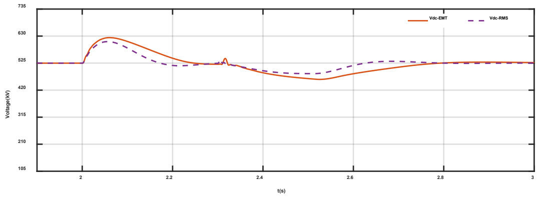
Three-phase instantaneous ac voltages at B1 and their magnitudes



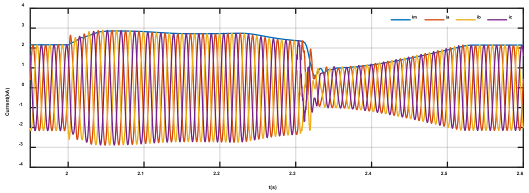
Magnitudes of three-phase ac voltages at B1



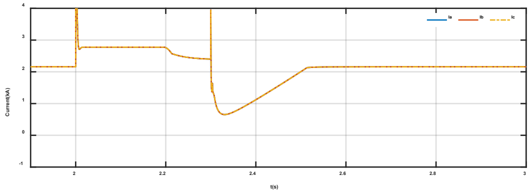
d-q currents



dc-voltage



Three-phase instantaneous ac currents and magnitudes



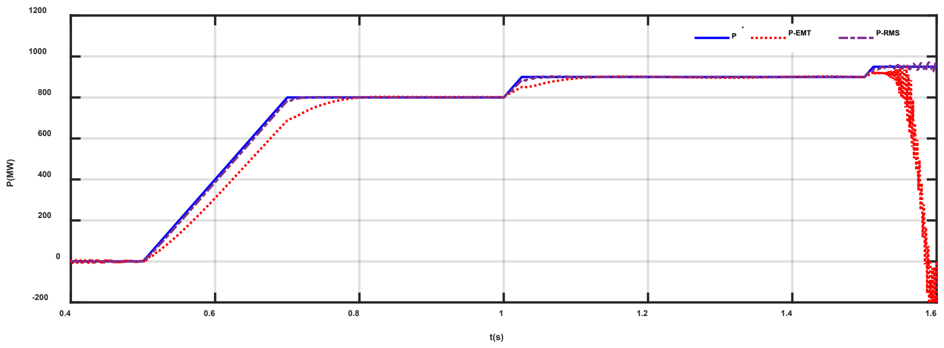
Magnitudes of three-phase ac currents

Fig. 8. One-to-one comparison of selected EMT and RMS simulation waveforms when VSC_2 is subjected to 300 ms three-phase-to-ground ac fault

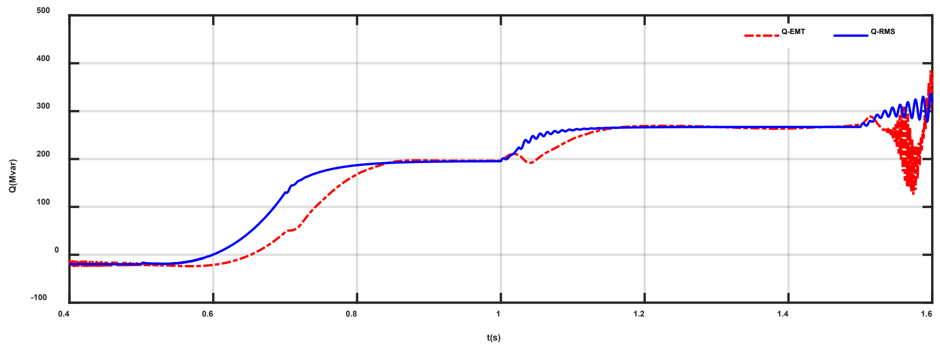
Summary:

- ✓ In pre-fault t<2 s, VSC_2 injects 1000 MW into B_2 and regulates ac voltage at B2 at 380 kV.
- ✓ At t=2 s, B2 is subjected to 300 ms three-phase ac fault.
- ✓ Observe the RMS and EMT equivalent waveforms are closely matched, including dc side dynamics.

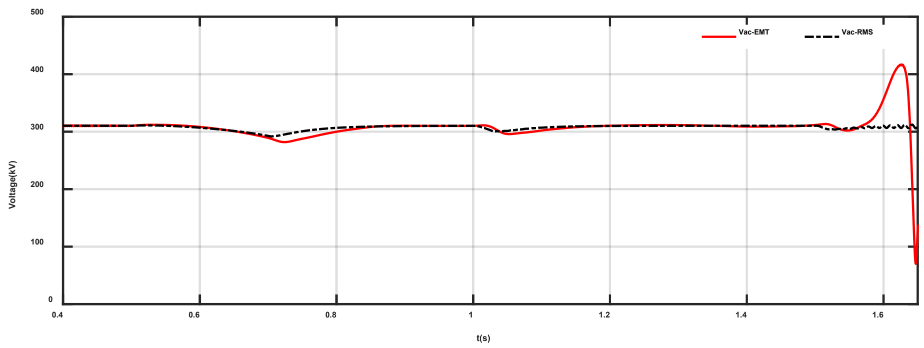
❑Impact of SCR



(a) Active power



(b) Reactive power



(c) Ac voltage

Summary:

- ✓ At t=0.5 s, VSC_2 ramps its active power injection into B_2 in step fashion while it regulates ac voltage at B2 at 380 kV.
- ✓ Observe both RMS and EMT waveform exhibit similar performance until the point of collapse. In per unit term, the observed point of collapse when SCR=1.5 is in line with reference [1].

1. Limitations of voltage source converter in weak ac networks from voltage stability point of view, which is accessible at :

https://d1wqtxts1xzle7.cloudfront.net/89750590/j.ijepes.2020.10589920220816-1-ncgsf1-libre.pdf?1660647792=&response-content-disposition=inline%3B+filename%3DLimitations_of_voltage_source_converter.pdf&Expires=1724823108&Signature=LDeSFIaE5NdAIrlI7CHW3FZIDvCk8~FSEldgtS-oN7hXHY60zmfZxORYuRIWu8AgM5tzYdfu78aLHxnElWCKbG7wwHQNsCBCsDmQpQCpwpXMTy8UfwGn~ih4t9tuwQPhd~6Dluz3RGcSBJdxttT0IH8UdcH2QfvXpNl2PlSuly8DgJI0-pFNVvu6H4NZXHWno7XZocH8Le86M4h6yiI3sU0KWAyGOh17KCMpnlSkxhZPH3WMr4anFtLDYTH99xITyp07x3iVOnd4WZhWz4ec8LU7tsh-T8AqZCpUmR7AxkcaYBm0mqLMl1WoSxGjS5w6eHN6yBroEoPqBKrg5ALEyw__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

❑Conclusion

In summary, it is concluded that the proposed VSC RMS mode (Grid Following Controlled)) is:

✓ Able to match the typical behaviour of the VSC EMT during:

  - Normal operation and step changes in active and reactive powers
  - Symmetrical and asymmetrical ac faults
  - Operation in weak ac network.

❑Future work

✓ To implement Grid Forming Controlled VSC RMS, considering both positive and negative phase sequency.

✓ To validate the developed model against EMT equivalent.