Large-Signal Stability Analysis of Self-Turn-On in Switching Transients

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Background and Motivation
- Switching behaviors of fast power semiconductors are sensitive to parasitic elements
- Previously self-turn-on phenomena are observed where MOSFETs are falsely turned on by the common source inductance during turn-off transient
- Existing analysis are based on either time-domain waveforms or small-signal modeling, but switching transients are highly nonlinear and large-signal

Technical Approach
- Formulating the Brayton-Moser mixed potential function which describes a circuit in a “energy gradient” form
  \[
  \frac{dx}{dt} = Q^{-1}(x) \cdot \frac{dP}{dx}
  \]
- Applying the large-signal asymptotic stability criteria
  \[
  \mu(\tilde{R}_1^s) + \mu(\tilde{R}_2^s) \geq \delta, \delta > 0
  \]
- Performing parametric study on self-turn-on phenomena to understand the root cause

Conclusions
- Switching transients are highly nonlinear and large-signal, but can be nicely described with mixed potential function
- The root cause of self-turn-on phenomena includes not only the common source inductance, but also the nonconventional voltage dependence of trench MOSFETs’ parasitic capacitance
### Mixed Potential Function

Given \( x = [i \ v]^T, i = [i_g \ i_d]^T, v = [v_{gs} \ v_{ds} \ v_{ka}]^T \), the circuit can be described as

\[
\frac{dx}{dt} = Q^{-1}(x) \cdot \frac{dP}{dx},
\]

where

\[
Q(x) = \begin{bmatrix}
-L(i) & 0 \\
0 & C(v)
\end{bmatrix},
\]

\[
L(i) = \begin{bmatrix}
L_g + L_s & L_s \\
L_s & L_d + L_s
\end{bmatrix},
\]

\[
C(v) = \begin{bmatrix}
C_{gs} + C_{gd} & -C_{gd} & 0 \\
-C_{gd} & C_{gd} + C_{ds} & 0 \\
0 & 0 & C_{ka}
\end{bmatrix},
\]

\[
P(x) = A(i) + B(v) + N(i,v),
\]

\[
A(i) = -V_g i_g - V_d i_d + \frac{1}{2} R_g i_g^2 + \frac{1}{2} R_d i_d^2,
\]

\[
B(v) = L_v i_{ka} + \frac{1}{2} G_M v_{ds}^2 + \frac{1}{2} G_D v_{ka}^2,
\]

\[
N(i,v) = v_{as} i_d + v_{gs} i_g + v_{ka} i_d.
\]

### Asymptotic Stability Criteria

Denote

\[
K_1(i,v) = \frac{1}{2} A_{ii}(i) + \frac{1}{2} ([A_i(i) + \gamma v]L^{-1}(i))_i L(i)
\]

\[
K_2(i,v) = \frac{1}{2} B_{vv}(v) + \frac{1}{2} ([B_v(v) - \gamma^T i^T C^{-1}(v)]_v C(v)
\]

Further denote

\[
\tilde{K}_1^s(i,v) = \frac{1}{2} L^{-\frac{1}{2}}(K_1 + K_1^T)L^{-\frac{1}{2}}
\]

\[
\tilde{K}_2^s(i,v) = \frac{1}{2} C^{-\frac{1}{2}}(K_2 + K_2^T)C^{-\frac{1}{2}}
\]

The sufficient but not necessary condition for asymptotic stability is

\[
\mu(\tilde{K}_1^s) + \mu(\tilde{K}_2^s) \geq \delta, \delta > 0
\]

and \( P(x) \to \infty \), as \( |x| \to \infty \), and \( \mu(S) \) means the infimum of the eigenvalues of \( S(x) \) over all \( x \)

* **Note** the asymptotic stability is a very “strong” stability requirement
Parametric Study of Large-Signal Stability

Relationship Between Time-Domain Waveforms and Mixed Potential Function
• Turn-off without obvious self-turn-on

Value of $\mu_1 + \mu_2$ for Different Cases
• Increase in common source inductance significantly worsens large-signal stability for IXKR47N60C5
• Unconventional capacitance voltage dependence is the other cause of instability

Parasitic Capacitances
IXKR47N60C5
C3M0065090D

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