Hybrid Modulators for conducted EMI suppression in modular-parallel topology

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1.- Introduction

The present trend in Power Electronics to improve performance is SYSTEM INTEGRATION

- Power density [kW/dm³]
- Power per unit weight [kW/kg]
- Relative cost [€/kW]
- Relative losses [%]
- Failure rate [h⁻¹]
1.- Introduction

EMI FILTER
1.- Introduction

- Switching Frequency Modulation (SFM) is a worthy way to suppress EMI in power converters.
- SFM applied to parallel arrangement should be combined with interleaving. This will result in Variable Delay Frequency Modulation (VDFM).
- This technique is suitable for new devices (SiC).

- Parallel arrangement is a disruptive topology that breaks frequency barrier. Moreover, Coupled Interleaved Multicellular Parallel Converters (CIMPC) show several advantages in terms of system integration and dynamic response.
- CIMPC require a SYMMETRIC operation.
2.- SFM in Parallel Arrangement

Breaks frequency barrier
Increased control dynamics
Redundancy without impairing reliability
2.- SFM in Parallel Arrangement

Periodic modulation function of period $T_m$
2.- SFM in Parallel Arrangement

<table>
<thead>
<tr>
<th>Modulations</th>
<th>$\varepsilon_{k,i}$</th>
<th>$T_{k,i}$</th>
<th>$\tau_{k,i}$</th>
<th>$\alpha_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDFM-Tm</td>
<td>0 $\forall i,k$</td>
<td>$T_c + \Delta T_k \forall i$</td>
<td>$D_c \cdot T_k \forall i$</td>
<td>$\frac{T_m}{N}(i-1)$</td>
</tr>
<tr>
<td>CDFM-Tc</td>
<td>0 $\forall i,k$</td>
<td>$T_c + \Delta T_k \forall i$</td>
<td>$D_c \cdot T_k \forall i$</td>
<td>$\frac{T_c}{N}(i-1)$</td>
</tr>
<tr>
<td>VDFM</td>
<td>$\frac{T_{k,i}}{N}(i-1)$</td>
<td>$T_c + \Delta T_k \forall i$</td>
<td>$D_c \cdot T_k \forall i$</td>
<td>0 $\forall i$</td>
</tr>
</tbody>
</table>

Periodic modulation function of period $T_m$
3.- Variable Delay Frequency Modulation

VDFM combines interleaving and SFM

\[ S_{CDFM-Tm}(w) = F \left\{ \sum_{i=1}^{N} q_i(t) \right\} = NAD_c \hat{\alpha}(w) + \sum_{n=1}^{\infty} \left[ \frac{A}{j \pi n} \right] \left\{ \frac{1-e^{-j2\pi n}}{1-e^{-N}} \right\} \sum_{k=1}^{L} \left[ e^{-j2\pi H_k} \left( 1 - e^{-j2\pi \tau_k} \right) \right] \hat{\alpha}(w-nw_m) = \right. \]

\[ = NAD_c \hat{\alpha}(w) + N \cdot E_{CDFM-Tm}(w) \sum_{n=1}^{\infty} \left[ \frac{A}{j \pi n} \sum_{k=1}^{L} \left[ e^{-j2\pi H_k} \left( 1 - e^{-j2\pi \tau_k} \right) \right] \hat{\alpha}(w-nw_m) \right. \]

\[ S_{CDFM-Tc}(w) = F \left\{ \sum_{i=1}^{N} q_i(t) \right\} = NAD_c \hat{\alpha}(w) + \sum_{n=1}^{\infty} \left[ \frac{A}{j \pi n} \right] \left\{ \frac{1-e^{-j2\pi n}}{1-e^{-NL}} \right\} \sum_{k=1}^{L} \left[ e^{-j2\pi H_k} \left( 1 - e^{-j2\pi \tau_k} \right) \right] \hat{\alpha}(w-nw_m) = \right. \]

\[ = NAD_c \hat{\alpha}(w) + N \cdot E_{CDFM-Tc}(w) \sum_{n=1}^{\infty} \left[ \frac{A}{j \pi n} \sum_{k=1}^{L} \left[ e^{-j2\pi H_k} \left( 1 - e^{-j2\pi \tau_k} \right) \right] \hat{\alpha}(w-nw_m) \right. \]

\[ S_{VDFM}(w) = F \left\{ \sum_{i=1}^{N} q_i(t) \right\} = NAD_c \hat{\alpha}(w) + \sum_{n=1}^{\infty} \left[ \frac{A}{j \pi n} \right] \left\{ \frac{1-e^{-j2\pi T_k}}{1-e^{-NT_k}} \right\} e^{-j2\pi H_k} \left( 1 - e^{-j2\pi \tau_k} \right) \hat{\alpha}(w-nw_m) = \right. \]

\[ \alpha_i=0 \ ; \ \tau_k \text{ control} \ ; \ T_k \text{ modulated} \ ; \ \varepsilon_k=(i-1)T_k/N \]
3.- Variable Delay Frequency Modulation

VDFM combines interleaving and SFM

\[ \alpha_i = 0 ; \; \tau_k \text{ control} ; \; T_k \text{ modulated}, \; \varepsilon_k = (i-1)T_k/N \]
3.- Variable Delay Frequency Modulation

Example of VDFM performance:

\[ N=4 ; f_C=300kHz ; m=6 \]
3.- Variable Delay Frequency Modulation

Example of VDFM performance:

\[ N=4 \; ; \; f_c=300\text{kHz} \; ; \; m=6 \]
4.- Coupled Interleaved Multicellular Parallel Converter

We need a **SYMETRIC** system in order to prevent couplers saturation, that could lead to a catastrophic failure.

**SYMETRIC**
- Construction
- Gates drive
- Switching
4.- Coupled Interleaved Multicellular Parallel Converter

Duty-cycle

For phase $N$

$$D_N = D_c \cdot (1 + \Delta D)$$
4.- Coupled Interleaved Multicellular Parallel Converter

\[ N=3 \quad ; \quad f_c=300kHz \quad ; \quad m=6 \]
4.- Coupled Interleaved Multicellular Parallel Converter

\[ N=4 \; ; fc=300kHz \; ; m=6 \]
4.- Coupled Interleaved Multicellular Parallel Converter

\[ N=6 ; f_c=300kHz ; m=6 \]
5.- Experimental Results

![Graph showing experimental results with frequency on the x-axis and amplitude on the y-axis. The graph compares different conditions labeled as ∆D=0%, ∆D=5%, ∆D=15%, and ∆D=25%. The amplitude values are given in dB.]
5.- Experimental Results

\[ \text{CIMPC } N=6 ; \text{ DC/DC ; } \text{Vin}=311V ; \text{Vout}=48V ; \text{Po}=250W \]
5.- Experimental Results

$N=6 \ ; \ fc=10kHz \ ; \ m=6$
5.- Experimental Results

\[ N=6 \; ; \; fc=10kHz \; ; \; m=6 \]
5.- Experimental Results

$LISN \ [\text{dBuV}]$

<table>
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<th>Frequency $[\text{Hz}]$</th>
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<tbody>
<tr>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^5$</td>
</tr>
<tr>
<td>$10^6$</td>
</tr>
</tbody>
</table>

$N=6 \ ; \ fc=10k\text{Hz} \ ; \ m=6$
5.- Experimental Results

![Graph showing conducted noise in dBuV vs. frequency in Hz for N=6, fc=50kHz, and m=6. Peaks at Nfc, 2Nfc, and 3Nfc are highlighted.]
5.- Experimental Results

![Graphs showing CM voltage (AC) and Output Voltage Ripple over time.](image)
5.- Conclusions

- VDFM could be applied successfully to CIMPC to suppress conducted noise

- New Devices (SiC, GaN) are candidates to use this technique

- Duty-cycle deviations (\(\Delta D\)) produce the following effects:
  - None at Nfc
  - Attenuation degradation is noticed below Nfc
  - Attenuation degradation increases with N

- Precise timing in gate-drive signals is a keypoint for this particular application