Realizable references anti-windup implementation for parallel controllers in multiple reference frames

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Introduction

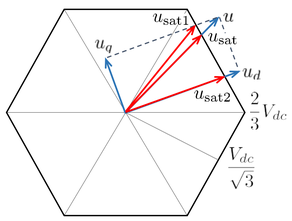
Parallel controller structures are often used for the control of harmonic components in power converters including harmonic compensation functions.

The harmonic compensation can be distorted during **saturation** of the power converter output.

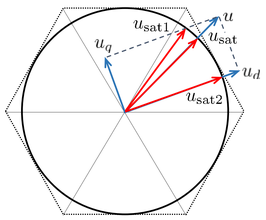
State-of-the-art methods drawbacks.
Either:
- Require gain tuning.
- Use of derivatives.
- Require special controller formulations or types.
- Intended only for stationary reference frame.

Goals:
- Implementation of the **realizable references anti-windup** technique suitable for **parallel controllers in multiple reference frames**.
- Do not require a particular type of controllers nor special formulations.
- Analysis of **different saturation options**.

Realizable references (single controller)



Hexagon voltage limit



Circle voltage limit

Controller difference equation: $u[k] = \sum_{i=0}^{n} b_i e[k-i] - \sum_{i=1}^{n} a_i u[k-i]$

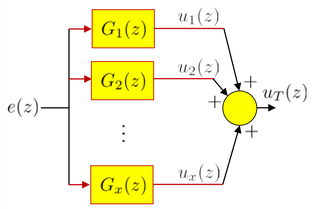
If $|u[k]| > |u_{sat}|$ the output is limited to u_{sat} and the error that would have exactly produced the saturated voltage is calculated:

$$e_{\text{sat}} = \frac{1}{b_0}\left(u_{\text{sat}} - \sum_{i=1}^{n} b_i e[k-i] + \sum_{i=1}^{n} a_i u[k-i]\right)$$

Alternatively, this simpler form is **proposed**:

$$e_{\text{sat}} = e[k] + \frac{1}{b_0}\left(u_{\text{sat}} - u[k]\right)$$

Realizable references (parallel stationary)



Controllers' difference equations:

$$u_1[k] = b_{1,0}\, e[k] + \sum_{i=1}^{n_1} b_{1,i}\, e[k-i] - \sum_{i=1}^{n_1} a_{1,i}\, u_1[k-i]$$

$$u_2[k] = b_{2,0}\, e[k] + \sum_{i=1}^{n_2} b_{2,i}\, e[k-i] - \sum_{i=1}^{n_2} a_{2,i}\, u_2[k-i]$$

$$\vdots$$

$$u_x[k] = b_{x,0}\, e[k] + \sum_{i=1}^{n_x} b_{x,i}\, e[k-i] - \sum_{i=1}^{n_x} a_{x,i}\, u_x[k-i]$$

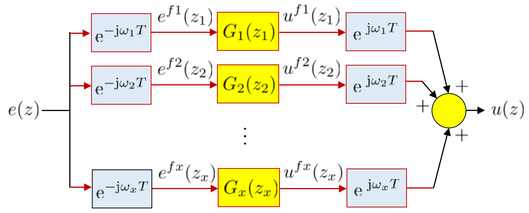
Controller global expression:

$$u_T[k] = \sum_{l=1}^{x} b_{l,0}\, e[k] + \sum_{l=1}^{x}\sum_{i=1}^{n_l} b_{l,i}\, e[k-i] - \sum_{l=1}^{x}\sum_{i=1}^{n_l} a_{l,i}\, u_l[k-i]$$

A **simple expression** can be calculated to obtain the **saturated error** signal, similar to the single controller case:

$$e_{\text{sat}} = e[k] + \frac{1}{\sum_{l=1}^{x} b_{l,0}}\left(u_{\text{sat}} - u_T[k]\right)$$

Realizable references (parallel synchronous)



Controllers' difference equations (synchronous ref. frame)

$$u_1^{f1}[k] = b_{1,0}\, e^{f1}[k] + \sum_{i=1}^{n_1} b_{1,i}\, e^{f1}[k-i] - \sum_{i=1}^{n_1} a_{1,i}\, u_1^{f1}[k-i]$$

$$u_2^{f2}[k] = b_{2,0}\, e^{f2}[k] + \sum_{i=1}^{n_2} b_{2,i}\, e^{f2}[k-i] - \sum_{i=1}^{n_2} a_{2,i}\, u_2^{f2}[k-i]$$

$$\vdots$$

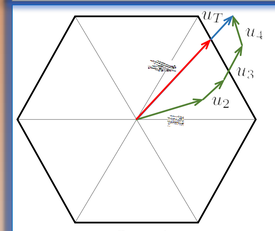
$$u_x^{fx}[k] = b_{x,0}\, e^{fx}[k] + \sum_{i=1}^{n_x} b_{x,i}\, e^{fx}[k-i] - \sum_{i=1}^{n_x} a_{x,i}\, u_x^{fx}[k-i]$$

Controller global expression (stationary ref. frame)

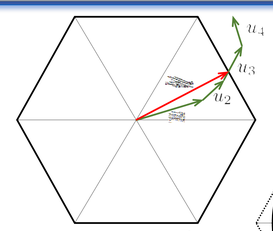
$$u_T[k] = \sum_{l=1}^{x} b_{l,0}\, e[k] + \sum_{l=1}^{x}\left(\sum_{i=1}^{n_l} b_{l,i}\, e^{fl}[k-i]\right) e^{\,j\theta_l[k]} - \sum_{l=1}^{x}\left(\sum_{i=1}^{n_l} a_{l,i}\, u_l^{fl}[k-i]\right) e^{\,j\theta_l[k]}$$

An **identical expression** to the stationary reference frame case can be obtained: $e_{\text{sat}} = e[k] + \frac{1}{\sum_{l=1}^{x} b_{l,0}}\left(u_{\text{sat}} - u_T[k]\right)$

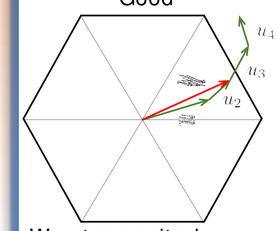
Analyzed saturation strategies



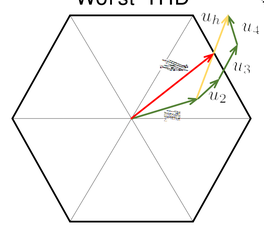
Good



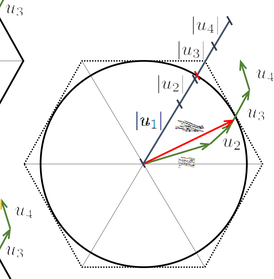
Worst THD



Worst magnitude error

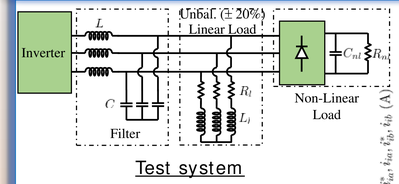


Best



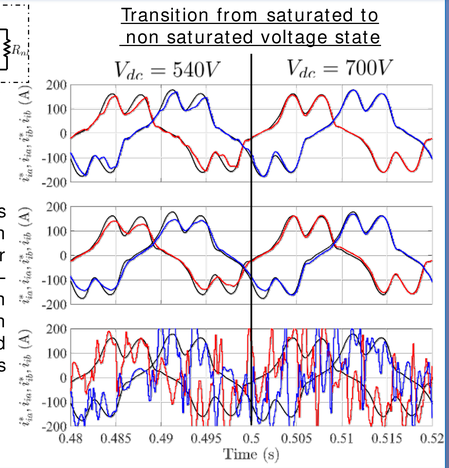
Simplest but second worst THD & mag. error

Simulation results



Test system

Realizables references (top) offers better response under saturation than limiting the individual controller outputs (no error back calculation – middle) and global output saturation (bottom). Moreover, the transition from saturated to non saturated state is the fastest. Five harmonics are controlled in this test.



Conclusions

Realizables references is an effective anti-windup method. This paper develops a simple implementation to be applied in parallel controller structures. It allows working in independent reference frames and combine different types of controllers. It allows the integration of different saturation strategies. Some strategies have been analyzed.

Contact

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