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(Authors' names and affiliation) First A. Author1 and Second B. Author2 are with the xxx Department, University of xxx, City, Zip code, Country, on leave from the National Institute for xxx, City, Zip code, Country (e-mail: author@domain.com).

Third C. Author3 is with the National Institute of xxx, City, Zip code, Country (corresponding author to provide phone: xxx-xxx-xxxx; fax: xxx-xxx-xxxx; e-mail: author@ domain.gov).

II. Introduction

Text of the introduction.

- minimum effort control - minimizing the control effort, where the effort is defined as maximum amplitude of the control [1]–[3]
- minimum effort control in robotics (kinematically redundant manipulators) [4]–[7],
- traditional control methods of power converters, carrier-based PWM techniques (sinusoidal, TIPWM) and space vector-based techniques (SVPWM).

III. Motivation and principles

A. Redundant Voltage Source Network

The problem of redundant voltage source network, degrees of freedom. Analogy to voltage source converters. Clarke's transform, A matrix, vector x as a vector of final voltages with minimum amplitudes.

$$\begin{aligned} x &= [\cdots]^T, \\ A &= [\cdots], \end{aligned} \tag{1}$$

Motivation -> minimize voltage needed.

B. Optimization problem definition

Linear system, minimum infinity norm, solution vector x. Primal problem definition...

$$\min_{\mathbf{Ax}=\mathbf{y}} ||\mathbf{x}||_\infty, \tag{2}$$

C. Solution using linear programming???

Note sure if this is to include in the paper......Solution using linear programming - linprog() in Matlab environment, suitable for mathematical modeling and rapid method development for any type of converter. Not effective for real-time application...

IV. Proposed Solution

A. Solution way for m (m + 1) matrices

.....

If matrix A is of size m (m + 1) and if its rank is m (its rows are independent), then we have

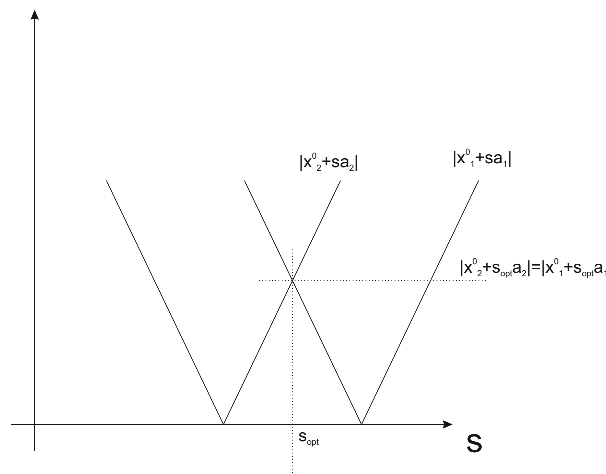
fx j Ax = yg = fx0 + sa j s 2 Rg; where x0 is an arbitrary point which satises Ax0 = y and a is a nonzero element of kernel of A (it satises Aa = 0). Then (1) is equivalent to minimize x;s kxk1 subject to x = x0 + sa; which amounts solving an optimization problem in one dimension minimize s kx0 + sak1: (3) For the the optimal solution of (3), there will be some indices i 6= j such that the components satisfy (x0 + sa)i = (x0 + sa)j : This have two solutions (if properly dened)

$$\begin{aligned} s^1 &= \frac{-x_i^0 + x_j^0}{a_i - a_j}, \\ s^2 &= \frac{-x_i^0 - x_j^0}{a_i + a_j}. \end{aligned}$$

Then among all these s, we select the one with minimal kx0+sak1. We summarize the procedure in Algorithm 1.1.

Algorithm 1.1 For solving (1) with one degree of freedom

Find some nonzero $\boldsymbol{a}$ such that $A\boldsymbol{a} = 0$
Find some $\boldsymbol{x}^0$ such that $A\boldsymbol{x}^0 = \boldsymbol{y}$
$f_{\min} \leftarrow \infty$
for i in $1 : m+1$ **do**
    for j in $i+1 : m+1$ **do**
        if $a_i \neq a_j$ **then** ▷ The ratio for s is properly defined
            $s \leftarrow \frac{-x_i^0 + x_j^0}{a_i - a_j}$
            if $\|\boldsymbol{x}^0 + s\boldsymbol{a}\|_\infty \leq f_{\min}$ **then**
                $f_{\min} \leftarrow \|\boldsymbol{x}^0 + s\boldsymbol{a}\|_\infty$
                $s_{\text{opt}} \leftarrow s$
            end if
        end if
        if $a_i \neq -a_j$ **then** ▷ The ratio for s is properly defined
            $s \leftarrow \frac{-x_i^0 - x_j^0}{a_i + a_j}$
            if $\|\boldsymbol{x}^0 + s\boldsymbol{a}\|_\infty \leq f_{\min}$ **then**
                $f_{\min} \leftarrow \|\boldsymbol{x}^0 + s\boldsymbol{a}\|_\infty$
                $s_{\text{opt}} \leftarrow s$
            end if
        end if
    end for
end for



B. Solution way for a general matrix A

....

When A is of a dierent size, then the kernel is no longer a line but a more dimensional spaces whose dimension equals to the degree of freedom. Denote the generators of this space by a1; : : : ; aK. Then we have again

$$\{x \mid Ax = y\} = \{x^0 + s^1a^1 + \ldots s^Ka^K \mid s^1, \ldots, s^K \in \mathbb{R}\}.$$

This means that (3) is replaced by

$$\operatorname*{minimize}_{s} \|x^0 + \sum_{k=1}^{K} s^k a^k\|_\infty.$$

...

Solution by ADMM

1 Solve the previous using ADMM

Create matrix $B = [a^1, \ldots, a^K]$ and vector $s = [s^1; \ldots; s^K]$. Then

$$\sum_{k=1}^{K} s^k a^k = Bs.$$

Problem (2) is equivalent to

$$\begin{aligned} &\underset{s,z}{\text{minimize}} && \|z\|_\infty \\ &\text{subject to} && x^0 + Bs - z = 0. \end{aligned}$$

Scaled augmented Lagrangian

$$L(s, z; \mu) = \|z\|_\infty + \frac{\rho}{2}\|x^0 + Bs - z + \mu\|^2$$

ADMM [1, Equations 3.5-3.7] is the iterative procedure

$$\begin{aligned} s^{k+1} &\leftarrow \underset{s}{\operatorname{argmin}}\, L(\cdot, z^k; \mu^k) \\ z^{k+1} &\leftarrow \underset{z}{\operatorname{argmin}}\, L(s^{k+1}, \cdot; \mu^k) \\ \mu^{k+1} &\leftarrow \mu^k + x^0 + Bs^{k+1} - z^{k+1}. \end{aligned}$$

1.1 Update for s

Minimizing L with respect to s is equivalent to minimizing

$$L(s, z; \mu) = \frac{1}{2}\|x^0 + Bs - z^k + \mu^k\|^2,$$

which is the standard quadratic regression with the closed-form solution

$$s^{k+1} = (B^\top B)^{-1} B^\top (z^k - x^0 + \mu^k).$$

Matrix $C := (B^\top B)^{-1} B^\top$ can be precomputed online.

...

...Problem solving requires high processing power, not very effective in real-time environment....

C. Solution of Dual Problem

... Duality of ℓ_1 and ℓ_∞ norm (D. G. Luenberger) [8]. Dual problem defined by Cadzow:

The Cadzow algorithm [9], [10] is based on a solution search of the associated dual problem

$$\max_{\|\mathbf{A}^T\mathbf{u}\|_1 \leqq 1} \mathbf{y}^T\mathbf{u} = \min_{\mathbf{Ax}=\mathbf{y}} ||\mathbf{x}||_\infty, \tag{3}$$

using the alignment property between final vectors $\mathbf{A}^T\mathbf{u}^0$ and $\mathbf{x}^0$ to evaluate $\mathbf{x}^0$:

$$\left[\mathbf{A}^T\mathbf{u}^0\right]^T \mathbf{x}^0 = \left\|\mathbf{A}^T\mathbf{u}^0\right\|_1 \left\|\mathbf{x}^0\right\|_\infty, \tag{4}$$

i.e.

$$\left\|\mathbf{x}^0\right\|_\infty = \mathbf{y}^T\mathbf{u}^0 = \left[\mathbf{A}^T\mathbf{u}^0\right]^T \mathbf{x}^0. \tag{5}$$

Primal problem

$$\begin{aligned} &\underset{x}{\text{minimize}} && \|x\|_\infty \\ &\text{subject to} && Ax = y. \end{aligned} \tag{1}$$

Dual problem

$$\begin{aligned} &\underset{u}{\text{maximize}} && y^\top u \\ &\text{subject to} && \|A^\top u\|_1 \leq 1. \end{aligned} \tag{2}$$

Dual problem enhanced

$$\begin{aligned} &\underset{u^+,u^-,z^+,z^-,w}{\text{maximize}} && y^\top u^+ - y^\top u^- \\ &\text{subject to} && A^\top u^+ - A^\top u^- - z^+ + z^- = 0, \\ & && \textstyle\sum(z_i^+ + z_i^-) + w = 1, \\ & && u^+, u^-, z^+, z^-, w \geq 0. \end{aligned} \tag{3}$$

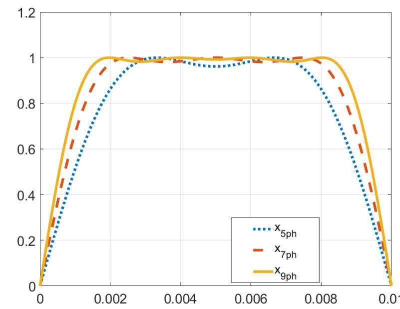


Fig. 1. Figure example

- All three problems are equivalent and they are linear problems.
- Each linear problem has a solution in an extremal point (corner) of its feasible set. The number of extremal points is finite.
- The solution set of (2) does not depend on y. Denote the finite set of extremal points by U.
- Previous two bullets imply the following: For every y, there is always some $u \in U$ which solves (2).
- I do not know how to compute the extremal points of (2) but there is a formula for computing the extremal points of (3).

This suggests that the way to go is to compute the extremal points of (3). Since they are in an enhanced space (u^+, u^-, z^+, z^-, w), we reduce them into the original space u corresponding to problem (2). This reduction will create a superset of the extremal points of (2). But there is a way of obtaining the set of extremal points of (2) from this superset.

V. Application/Control of Power Converters)

A. Traditional three-phase converters

Conventional three-phase converters, correlation to SVPWM and

B. Three-phase four-leg converters

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C. Multilevel converters

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D. Multiphase converters

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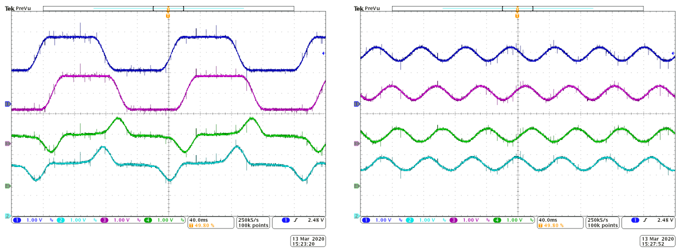
VI. Experimental results

Some experimental results.

VII. Conclusion

Conclusion Text text text. Text text text. Text text text. Text text text. Text text text. Text text text. Text text text. Text text text. Text text text. Text text text..



(a) Fundamental with 3^{rd} , 5^{th} , and 7^{th} harmonic component.

(b) 3^{rd}harmonic component only.

Fig. 2. Example of experimental results

Appendix
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Acknowledgment

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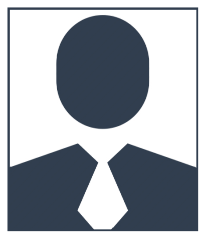

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