Vector Control in Uninterruptible Power Supply Systems (UPS)

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0. Introduction

To control the output voltage of uninterruptible power supplies (UPS), instantaneous value related methods are usually used. These are known for their restrictions (determined by the system) at non-linear loads and in parallel operation. To meet the requirements, this basic control concept therefore uses several additional complex components.

A mathematical representation specially suitable for calculations in three-wire and four-wire systems is called "space vector". Such systems often occur in power distribution engineering and drive technology (distribution of electrical energy via three-phase systems, three-phase transformers, three-string synchronous and asynchronous drives). A representation with the help of space vectors allows a straightforward, clear and often illustrative description and calculation of both stationary and dynamic processes in these fields. The space vector transformation is a newer calculation method which has gained importance over the past few years, especially when describing dynamic processes in three-phase a.c. machines.

This article is intended to show the advantages of using space vector representation in controlling UPS. The above described disadvantages of conventional controls do not occur when resorting to this approach.

1. Introducing the Terms of Vector Control

1.1. The Space Vector Transformation (SVT)

The SVT describes the coordinate transformation of three time-dependent values. The resulting values consist of a complex element, the so-called space vector and a scalar zero sequence component (short: zero component). The transformation equations are defined as follows:

\[
\text{space vector: } v(t) = \frac{2}{3} \left[ v_u(t) + a \cdot v_r(t) + a^2 \cdot v_w(t) \right]
\]

\[
\text{zero component: } v_z(t) = \frac{1}{3} \left[ v_u(t) + v_r(t) + v_w(t) \right], \text{ with } a = e^{\frac{2\pi}{3}}
\]

(eq. 1-1)

For the representation of the vector-valued space vector we have chosen the preferably used underscore arrows.

To keep the different amplitude values comparable, the signals \( v_r(t) \), \( v_s(t) \) and \( v_r(t) \) refer to the maximum value of a sinusoidal signal which has the rms value \( V_{nom} \).

\[
v_X(t) = \frac{V_X(t)}{V_{nom} \cdot \sqrt{2}}, \text{ with } X = R, S, T
\]

(eq. 1-2)

The spin operator \( \hat{a} \) causes the time signals to be projected onto axes rotated by 120° or \( \frac{2}{3} \pi \text{ rad} \) respectively.
For the operator, the following relations apply:

\[ 1 + a + a^2 = 0 \]
\[ a^{3n+1} = a^n, \quad \text{for } n = 0,1,2... \]  

(eq. 1-3)

The space vector is defined for any time signals. Compared to these when looking at three-phase systems, the space vector transformed values have favourable characteristics. If one assumes for example, purely sinusoidal time signals with the same amplitude and frequency which are phase-shifted by 120° each,

\[
v_\nu(t) = \hat{v} \cdot \cos(\alpha x)
\]

\[
v_\nu(t) = \hat{v} \cdot \cos\left(\alpha x - \frac{2}{3} \pi\right)
\]

\[
v_\nu(t) = \hat{v} \cdot \cos\left(\alpha x + \frac{2}{3} \pi\right)
\]

the following is obtained for the space vector values:

\[
v(t) = \frac{2}{3} \cdot \hat{v} \cdot \frac{1}{2} \left\{ \left(1 + a \cdot a + a^2 \cdot a\right) \cdot e^{j\alpha x} + \left(1 + a \cdot a + a^2 \cdot a\right) \cdot e^{-j\alpha x} \right\} = \hat{v} \cdot e^{j\alpha x}
\]

\[
v_z(t) = \frac{1}{3} \cdot \hat{v} \cdot \frac{1}{2} \left\{ \left(1 + a + a^2 \right) \cdot e^{j\alpha x} + \left(1 + a + a^2 \right) \cdot e^{-j\alpha x} \right\} = 0
\]  

(eq. 1-5)

This shows that the space vector of a symmetrical, ideal sinusoidal three-phase system during one period describes a 360° turn with a mathematical positive spin direction, whereas the vector length is constant. The zero component in that case always equals zero.

This symmetrical case in three-phase systems is an ideal state for the use in power engineering. The space vector representation is especially interesting, since in the symmetrical case, the state of the system can be described with a single (complex) value. Thus, three-phase relations can be represented in a well structured manner by means of single-phase equivalent circuit diagrams. The space vector system contains complex value voltages and currents, whereas the zero system contains scalar ones.

If the voltages are no longer purely sinusoidal, but contain harmonic components of higher order, they can affect the space vector as well as the zero system. In the following we will be discussing which important harmonics affect which part of the space vector components.

1.2. Zero Components in the Three-phase Systems

It depends first of all on the topology of the system used, if a zero component exists at all. When for example, one looks at the line currents in the three-wire system, the following condition must apply:

\[ i_\nu(t) + i_\delta(t) + i_\gamma(t) = 0 \]  

(eq. 1-6)
This means that the zero component of the currents space vectors in this case always equals zero. The above condition can also be valid in a system with a neutral line (four-wire system), if the strain on the individual wires is symmetrical. Thus, the zero component is often called the unsymmetrical part of the space vectors.

But, with symmetrical strain in the four-wire system, currents can also occur in the neutral line which are caused by harmonic components on the fundamental frequency current.

Some of these currents usually occur in the zero system. Figure 1 shows the overlaying of the harmonic current components at the neutral line in a four-wire system, depending on the order. It is assumed that the harmonic has, in relation to its fundamental mode, the same phasing in all three time signals. (This is usually true in practice.) One can recognize that only the multiples of three (3., 6., 9., etc.) provide values that are different from zero. Therefore it can be noted that besides the unsymmetrical harmonic components, usually harmonics with an ordinal number being a multiple of three occur at the zero component.

1.3. Harmonic Components in the Space Vector

It is easy to see from the last paragraph that the space vector value (besides the symmetrical harmonic components of the three-phase system) contains those harmonics that are not a multiple of three (also assuming that the harmonic components have, in relation to their fundamental mode, the same phasing in all three phases).

Figure 2 shows a simulation of a six-pulse current space vector which contains harmonic components of the 5th and 7th harmonic. The locus has a typical hexagonal shape.
1.4. Adapted Coordinate Systems

A suitable coordinate system is necessary to be able to determine certain harmonic components in the space vector. In a system rotating with a special angular frequency $\omega_N$, the harmonic component matched with this frequency constitutes a static vector which is overlayed by other harmonic components that form a locus of the cumulative vector. Based on the space vector representation in polar coordinates,

$$\mathbf{v}(t) = \mathbf{a}(t) + \mathbf{b}(t) = |\mathbf{v}(t)| \cdot e^{j\varphi(t)}, \quad \text{with } \varphi(t) = \arctan\left(\frac{\beta(t)}{\alpha(t)}\right)$$  \hspace{1cm} (eq. 1-7)

the new space vector is:

$$\mathbf{v}_{\omega_N}(t) = |\mathbf{v}(t)| \cdot e^{j\varphi(t)} \cdot e^{-j\omega_N t}$$  \hspace{1cm} (eq. 1-8)

By calculating the balance point vector of the locus, one obtains the harmonic component of the harmonic rotating at the frequency $\omega_N$. 
2. Vector Control in UPS Systems

2.1. Demands Placed on a UPS Inverter

An UPS must be able to prevent any irregularity in the power supply or bridge power outages until the load can be powered down in a controlled manner. There are several ways of realizing these possibilities: batteries serve as storage capacity for the bridging energy. To bridge shorter periods, spin-mass energy storage is used.

One of the most demanding, yet most flexible concepts is the so-called on-line UPS with double-conversion technology, i.e. with a permanently active inverter. Its main advantage lies in the fact that the generation of the load voltage is independent of the feeding mains. Thus, in addition to its original function, this system allows an active power conditioning, i.e. that supply fluctuations (also short term ones) can be kept away from a sensitive load. The most important element of such a system is the inverter which turns d.c. voltage into a three-phase a.c. voltage at the UPS output.

Figure 4 illustrates the principle design of a three-phase on-line UPS with a pulse-width-modulated inverter (PWM inverter). The representation of assumed time signals together with the loci of the complex space vectors makes it clear how disturbances at the time values affect the space vector. One turn corresponds to one fundamental wave period of the time signals assumed as periodical.
What are the advantages of vector values for the use in UPS? First, one must look more in detail at the functions of a modern UPS. The control of high quality UPS, and above all, the control of the output inverter must meet the following requirements:

- compliance with a narrow static voltage tolerance at the output with as few harmonic components as possible in all operating situations.
- phase-synchronous operation of the UPS output with the feeding mains to be able to switch to it anytime without any switching gap.
- controlling inrush-currents of transformers (decreasing DC parts), non-linear loads, motor loads.
- high short-circuit power and fast relaxation of output voltage (to ensure the selectivity of load circuitry).
- redundancy through parallel operation (control of current balancing and synchronization of the inverters).
- generation of voltages without a DC component for operation with transformers and inductive loads.
- suppression of voltage harmonics caused by non-linear loads (low output impedance especially at the 3\(^{rd}\), 5\(^{th}\), 7\(^{th}\) harmonic).

Figure 5 shows the detailed structure of a three-phase on-line UPS.
harmonic currents
filter (optional)
rectifier inverter (INV) battery
coupling battery

Manual

Bypass

autom. bypass

AC/AC converter

output filter

INV switch

Manual Bypass

Figure 5: Block diagram of an on-line UPS

On the mains part, controlled or uncontrolled rectifiers in 6-pulse or 12-pulse version are used. To keep the mains feedback by non-sinusoidal input currents low, optional filter circuits are inserted besides the commutating choke, especially at 6-pulse rectifiers. They are inserted for the essential harmonic currents (with six-pulse bridges at a fundamental of 50 Hz, especially the 5th harmonic at 250 Hz).

The automatic bypass has to ensure that in case of problems with the inverter, the feeding mains can be switched to quickly, and without any gap. In such a case the load supply is no longer battery-buffered. But there is no immediate load cutoff, thus allowing for a reaction to the malfunction. On the other hand in some operating situations, with an automatic bypass the feeding mains can be used to support the inverter. This is especially useful in the case of an overload or short circuit, since the inverter can only carry a restricted maximum current.

The following values are “state of the art” for such systems:

- **at linear, symmetrical load:**
  - static voltage tolerance: 1 %
  - Angular displacement: < 1° el.

- **unbalanced load, unsymmetrical load:**
  - voltage tolerance: 4 %
  - Angular displacement: < 5° el.

- **at non-linear load according to [5]**
  - harmonic distortion at the output voltage: 5 %

**dynamics**
  - control transition time in case of malfunction: 10 %

### 2.2. Realization

#### 2.2.1 Structure of the Vector Control

To determine a space vector of a three-phase system, you normally have to take into account a minimum effort. It makes no sense e.g. for currents to measure all three values, if
these values satisfy eq. 1-6. In practice, usually two voltages and two currents respectively are measured.

Figure 6: UPS vector control structure

Figure 6 shows a possible control structure for an on-line UPS with an integrated automatic bypass which uses coordinate transformation.

With the use of digital signal processors (DSP), the realization of very complex control structures with flexible adapting mechanisms is possible. The instruction set of a DSP makes it possible to realize a coordinate transformation (this is nothing more than a static conversion of the actual value) with a few commands. Thus a representation suitable for the task to be performed can be chosen in every part of the controller. The operating situation of the three-phase UPS is influenced by many values. The parameters of main influence are the output voltages; the manipulated variables at the PWM inverter are the pulse patterns for the control of the semiconductor switches (mostly IGBTs).

The greatest influence on the output voltages is exerted by the output currents whose waveform can be, depending on the loads, extremely non-linear distorted compared to the voltages. The d.c. voltage at the input of the inverter acts as a disturbance variable. The magnitude and the harmonic content of the d.c. voltage have a strong influence on the actuating reserve of the inverter. Additional voltage acquisitions, such as the PWM currents at the output of the inverter (see Figure 4) and the balancing currents in parallel systems provide additional information which can be used to protect the system as well as for better control dynamics.

This great amount of actual values, most of them three-phase, creates enormous amounts of data which, with a time-signal based control can only be mastered with difficulty. The vector transformation reduces the data and concentrates control on the essential part of the information without restricting the capability of influence on the system.

2.3. Mains Synchronous and Self-Clocked Operation

In mains synchronous operation, the control unit orients the output of the UPS regarding frequency and phasing at the feeding mains to be able to support the output via the automatic bypass, if needed, in the case of an overload or short circuit. The amplitude and waveform are generated by an internal reference so the UPS works independently of input...
mains voltage distortions. This ensures low harmonic distortion at the output voltage. Information on frequency and phasing are very easily extracted from the space vector transformed actual values. With a representation in polar coordinates, $\varphi$ is directly indicated. The basic frequency can be calculated as a smoothed $\Delta \varphi / \Delta t$.

![Diagram of UPS systems](image)

**On-Line UPS synchronous to mains, bypass enabled**

**On-Line UPS self-clocked, bypass disabled**

Figure 7: Mains synchronous and self-clocked on-line UPS

If the output voltage leaves its specified tolerance range (e.g. $U_{\text{NOM}} \pm 15\%$ regarding the voltage and $f_{\text{NOM}} \pm 3\%$ regarding the frequency), the control unit switches to self-clocked operation. This means that the UPS only orients itself by its internal reference (see Figure 7 below), which does not mean that energy is taken from the battery at this stage. For example, if there are frequency fluctuations in the feeding mains, the mains is still able to supply the loads from the viewpoint of the power flow, but in self-clocked mode an output support by the feeding mains is not possible any more. The UPS prevents the modified frequency from having negative effects on the loads. Though normally this does not occur with public mains, since the load state of the mains is controlled by a very narrow frequency bandwidth. However, the above mentioned case can play an important role in diesel-driven operation.

The mechanisms for identifying a power outage, i.e. when the feeding mains is no longer able to supply enough energy for the loads, are different according to the UPS type. Some systems orient themselves by the intermediate circuit d.c. voltage, others go by the three-phase input mains.
2.3.1 Redundant Systems

Applications that place extremely high demands on reliability need more than one UPS to supply the overall load. Like with all other electronic devices, failures are possible. Therefore, for such systems it is indispensable that the concept of the UPS provides for parallel operation. On the one hand, higher output performances can be realized. On the other hand, several single units can be connected to provide redundancy, e.g. \((n+1)\) operation. Therefore, a single unit can fail anytime without putting the customer at risk.

![Diagram of Parallel UPS System]

**Figure 8: Parallel UPS system, balancing current**

The parallel connection allows a well directed adaption of the power supply concept to the safety requirements of the UPS user. The existence of this possibility is of utmost importance for any UPS system, and especially for those with higher performance. Figure 8 illustrates the basic configuration of two single UPS units into a parallel system. The output currents should be equally distributed between the two single units. With the use of vector values the handling of such constellations is simplified. It is especially the representation in polar coordinates that always provides information regarding amplitudes and phasing of the values in the parallel system.

The problem of parallel systems lies in the fact that component tolerances cause balancing currents between the single units. These currents are a strain on the inverter without contributing to the supply of the loads. The task of a paralleling controller (see Figure 6) consists in keeping these currents to a minimum to optimize the usable performance of the total system.

One approach to the parallel connection is the Master-Slave concept. One system takes on the leading role, “Master” and the other parallel units, “Slaves”, orient themselves by the output voltage of the Master unit. The disadvantage of this concept lies as follows: in case of
the failure of the Master unit, the system becomes “leaderless”, for example, load changes (as they can occur with the failure of the unit, too) can result in a load cutoff.

By means of the Vector Control a paralleling concepts can be realized, where each unit has the same status in the UPS system: when being hooked up, the single units can be led to steady phase relations (synchronous operation), at which a simultaneous start of the single blocks on the secure bus is possible, any unit being able to continue running smoothly in case of failure. Additionally, by precisely setting the manipulated vectors of every inverter, the balancing currents can be minimized and the strain on the output of the parallel system can be reduced. This solution requires straightforward communication between the single units.

2.3.2 Waveform Correction

The value set by the master controller (see Figure 6), is determined by an internal reference signal (mains synchronous or self-clocked). Parallel systems additionally have to refer to the balancing currents. The design of this controller is most important for the dynamics of the total system. Additional modules described as a waveform correction in Figure 6, ensure low output harmonic distortion in stationary operation. These modules work dynamically with higher time constants than the master controller to prevent any influence on the stability of the control unit. The waveform of the set value is influenced in these modules. By knowing the controlled system at the UPS output (neutral grounding transformer, PMW switching frequency filter), the pulse pattern of the semiconductor can be influenced to keep harmonic distortion low. Possible functions are:

- influencing certain harmonic components. By changing the coordinate system, the harmonic components can be easily identified off the space vector components (e.g. 3rd, 5th, 7th harmonic).
- realizing flexible control systems for high stability and accuracy (e.g. state regulator, adaptive regulators).

The waveform correction can be undertaken according to various criteria. Its structure is more complex than that of the master controller, but the manner of the correction has enormous effects on the harmonic content of the output voltage.

3. Measurements and Comparison of Different Control Concepts

The direct comparison of UPS systems with or without Vector Control shows the advantages of the presented concept compared to the conventional three-phase control. The measuring was done during stationary operation with special load situations:

- linear unsymmetrical load
- non-linear load (according to [5], appendix M.5)

For the measurements, UPS systems with the same nominal power (20 kVA at a performance factor of 0.8 inductive) and comparable application areas were used.
3.1. Definition of THD (the value to describe the quality of electrical power)

A harmonic analysis (Fourier transformation) is used for the quantitative description of electrical power quality. As a function of time, a non-sinusoidal Fourier series can be written as follows (applies to the current similarly):

\[ v(t) = V_0 + v_1 \sin \omega t + \sum_{n=2}^{\infty} v_n \sin(n \cdot \omega t + \phi_n) \]  

(eq. 3-1)

where
- fundamental wave \( v_1 = v_1 \sin \omega t \)
- angular frequency \( \omega = \frac{2 \cdot \pi \cdot f}{V_0} \), arithmetic mean
- d.c.component \( V_0 \)
- ordinal number \( n \).

The quality of electrical power is internationally judged by the value THD (total harmonic distortion factor) of the voltage and the current respectively. The THD value is defined by, /7/:

\[ THD = \sqrt{\sum_{n=2}^{\infty} \frac{v_n^2}{v_1^2}} \]  

(eq. 3-2)

The reference value is the rms value of the fundamental sinewave.

3.2. Unsymmetrical linear load

The UPS is strained by an ohmic resistance between two wires. If one assumes the voltages to be sinusoidal and the strain to be purely ohmic, the unsymmetrical load causes a counter system for the currents. It is important to pay attention to the symmetry in phase and amplitude of the three line voltages. Independent of the magnitude of the load, the advantages of a control based on the space vector representation are found here. Even a well optimized "instantaneous value control" with static magnitude controller shows a tolerable deviation at high loads.

![Figure 9: UPS with linear unsymmetrical load](image-url)
Figure 9 shows the experimental setup. The ohmic load is connected between the phases U3 and V3 at the output. Thus the phase U3 “sees” a load with capacitive component, the phase V3 “sees” a load with inductive component. Phase W3 remains unstrained. This kind of load puts high demands on the unbalanced load capability of the control. The representation of the voltage space vector for ca. 100 % load at the output of the UPS (see Figure 10), shows the unsymmetrical distribution of the three voltages with an instantaneous value control. The UPS controlled by vector control shows an equal amplitude distribution for all phases which is confirmed by the characteristic values in Table 1. Especially at high loads, with actuating limits already complicating the control, the vectorial processing shows its advantages. The equal distribution of most errors to all three phases has its cause in the direct relation of phases through the space vector.

With instantaneous value control, to keep the effort for the control to a minimum, individual phases are often left out, since symmetrical relations can usually be assumed on the whole system. In those cases where this assumption does not apply, significant deviations that cannot be compensated by the control unit can be seen at the output.

The detailed results of measurements with unsymmetrical linear load:

<table>
<thead>
<tr>
<th>Load</th>
<th>Amplitude deviation with Masterguard Vector Control in %</th>
<th>Amplitude deviation with static magnitude controller in %</th>
<th>Phase deviation with Masterguard Vector Control in °</th>
<th>Phase deviation with static magnitude controller in °</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 %</td>
<td>0,03</td>
<td>0,03</td>
<td>0,4; 0,1; 0,3</td>
<td>3,7; 0,3; 2,9</td>
</tr>
<tr>
<td>100 %</td>
<td>0,04</td>
<td>0,8</td>
<td>0,4; 0,5; 0,3</td>
<td>3,6; 0,5; 3,3</td>
</tr>
</tbody>
</table>

Table 1: Amplitude and phase deviation at unbalanced load

### 3.3. Non-linear symmetrical load

In this measurement a non-linear reference load according to ENV50091-3 (see [5], appendix A) is connected to the output of the UPS. For three-phase systems, this load consists of three single-phase B2 bridge circuits. For the experimental setup see Figure 11.
Seen here is a significant distortion of the waveform of the voltage space vector towards a six-pulse system. The space vector of the instantaneous value control shows weakness in phase V where the amplitude is significantly smaller than at the other two phases. On the whole, the space vector graph is much closer to the ideal circle outline.

Figure 13 and Figure 14 show the time signals of the output voltages and of an output current (on the phase U3). The current wave has a calculated Crest Factor of 2.7 at the instantaneous value control and 2.9 at the vector control respectively.
Especially in such operating conditions the advantages of the vector oriented control are revealed. The instantaneous value control makes clear that by the time-signal- based evaluation, the dynamics of the system distorts the voltage waveform. In the phase range in which the load current flows, the voltage is distinctly distorted. This is also proved by a rise in rms values. The waveform correction at the vector control provides a result that is distinctly closer to the sinusoidal shape without influencing the rms value of the voltage. The well directed influence on certain harmonic components significantly reduces the harmonic content.

Figure 13: Time signals voltage-current, instantaneous value control with non-linear load

Figure 14: Time signals current-voltage, vector control with non-linear load
This becomes clear at the THD as the characteristic value for the whole harmonic component (see Table 2). With both control methods, there is a significant difference in the values of the medium and high load range.

<table>
<thead>
<tr>
<th>Load</th>
<th>THD in string R in % Masterguard S</th>
<th>THD in string S in % Masterguard S</th>
<th>THD in string T in % Masterguard S</th>
<th>THD in string R in % Conventional UPS</th>
<th>THD in string S in % Conventional UPS</th>
<th>THD in string T in % Conventional UPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 %</td>
<td>2,8</td>
<td>2,8</td>
<td>2,8</td>
<td>6,4</td>
<td>8,8</td>
<td>6,1</td>
</tr>
<tr>
<td>100 %</td>
<td>4,4</td>
<td>4,6</td>
<td>4,3</td>
<td>11,7</td>
<td>15,6</td>
<td>11,3</td>
</tr>
</tbody>
</table>

Table 2: voltage THD values at non-linear load

4. **Summary and Outlook**

The application of Vector Control in UPS systems, as opposed to a conventional, phase-related control, especially shows advantages in case of the interaction between the single phases. Since the three-phase system (when neglecting the zero component) is represented by a (even if complex) value, this context is system immanent. If phase relations are important as in the parallel mode, a vector control has advantages. In this case, the vector control provides the control unit with information on amplitude, phase and frequency in a very simple manner.

Modern information technology as well as high availability of micro controllers and digital signal processors provide us with the necessary tools to enable us to use the above mentioned advantages even with lower cost products. With the further development of the integration of such flexible processing technologies, more complicated growing solutions can be realized. Especially in the UPS area, the development of new mathematical methods sets itself into the main position for the optimal power supply in a wide range of operating situations and automatic adapting to various loads.
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