SINGLE TUNED HARMONIC FILTER DESIGN AS TOTAL HARMONIC DISTORTION (THD) COMPENSATOR

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ABSTRACT

We know that the rise of Harmonics in the 20 kV distribution systems because of non-linear loads supplied by the distribution system. Harmonics consist of: a) the current harmonic distortion (THDi), b) voltage harmonics distortion (THDv).
The current total harmonic distortion (THDi) and voltage total harmonic distortion (THDv) technically can cause harm to the company’s impact power producers, among others: a) In the transformer increased burden losses, decreased able, shorten the operating life. b) On the increasing conductor loss in the network, c) Measurement of energy tends to be inaccurate on a kWh-meter mechanical (type flux), etc.
Arc furnace Customers is one of the biggest causes of customer onset of harmonics, especially the current total harmonic distortion (THDi). One way to limit the current total harmonic distortion (THDi) at 20 kV distribution system, namely: the end-user customer limit-current harmonics injected into the 20 kV distribution system. The current total harmonic distortion (THDi) that are injected into the 20 kV distribution system can be reduced, one of them by using a harmonic filter. There are an active filter and passive filter, with economic considerations passive filter is the best option to reduce the level of harmonics in the 20 kV distribution system. In this paper author takes the object under study is a customer arc furnace of 20 kV with an installed Power of 3,465 KVA.

Index Terms — power quality, harmonics, non-linear loads, filter, standards.

INTRODUCTION

The announcement of a ban on export of unprocessed metals and non-metallic minerals in the Minister of Energy and Mineral Resources ("MEMR") Republic of Indonesia, Regulation No. 7 of 2012 regarding the Improvement of Mineral Added Values Through Mineral Processing and Refining has made numbers mineral mining company began planning to build mineral processing plants into advanced products. The plan has sparked a growing demand for electric power supply for operation of the metal ore smelting plant in numbers of areas that rich in mineral resources.
Recently, there are already 10 potential customers have applied for electricity connection in south east Sulawesi, West Kalimantan, Ternate and East Nusa Tenggara region.
Condition of power quality and power supply reliability might be influenced by the bad performance of devices used in electricity power supplier company as well as those of end users, such as: arc furnaces, arc welders, etc. One characteristic of power qualities in steady state is harmonic. Harmonic consists of: a) Total harmonic distortion of current (THDi), b) Total harmonic distortion of voltage (THDv).
The current total harmonic distortion (THDi) and voltage total harmonic distortion (THDv) technically can cause harm to the company’s impact power producers, among others: a) In the transformer increased burden losses, decreased able, shorten the operating life. b) to conductor, it can cause network loss, voltage distortion and increase dielectric stress of the wire by which shorten its lifespan, c) Measurement of energy tends to be inaccurate on a kWh-meter mechanical (type flux), d) it causes thermal stress toward isolation giving impact to decrease the motor isolation life, e) to power system, it causes neutral current bigger that cause touch voltage bigger too so it is dangerous for main station operator, etc.
Arc furnace Customers is one of the biggest causes of customer onset of harmonics, especially the current total harmonic distortion (THDi). One way to limit the current total harmonic distortion (THDi) at 20 kV distribution system, namely: the end-user customer limit-current harmonics injected into the 20 kV distribution system. However, the current total harmonic distortion (THDi) that are injected into the 20 kV distribution system can be reduced or eliminated one of them by using a harmonic filter, where the current harmonic distortion corrected by a harmonic filter, so waveform approach as the initial wave form (fundamental).
The use of the harmonic filter requires additional costs, harmonic filter can be supplied by a power-user customer or provider of electric power (utility).
There are an active filter and passive filter, with economic considerations passive filter is the best option to reduce the level of harmonics in the 20 kV distribution system.
In this paper author takes the object under study is a customer arc furnace of 20 kV with an installed Power of 3,465 KVA, supplied from 31.5 MVA power transformer 150 kV / 20 kV Sei Rotan substation Medan – North Sumatera – Indonesia.
**DETERMINE DESIGN OF HARMONIC FILTER**

Steps to determine the capacity of harmonic filters with single-tuned filters in order to 20 kV and 0.4 kV bus, as shown in figure 1.

1. **Determine the level of the individual harmonics of the field measurement:** $I_h$ for $h = 3, 4, 5, \dots$

2. **Whether the IEEE 519-1992 Standard:**
   - **YES:**
   - **NO:**

3. **FILTER DESIGN**

4. **DETERMINE:**
   - **PF**, **QF**, **XF**, **\( X_h \), **\( X_h \), **\( X_h \)
   - **\( X_h \), **\( X_h \), **\( X_h \), **\( X_h \), **\( X_h \)
   - **\( X_h \), **\( X_h \), **\( X_h \), **\( X_h \), **\( X_h \)

5. **Whether the IEEE 519-1992 Standard:**
   - **YES:**
   - **NO:**

6. **Determine the effective capacity of reactive power filter** $Q_{\text{eff}} = S \times \left[ \sin(\cos^{-1}p_f) - \sin(\cos^{-1}p_f) \right]$ (1)
   - **Where:** $S =$ Customer Install Capacity

7. **Item 3. Determine the frequency tuning filters:**

8. **Item 4. Determine impedance of effective filter** $X_{\text{eff}} = \left( V_{\text{LL}} \right)^2 / Q_{\text{eff}}$ (2)

9. **Item 5. Determine capacitive and inductive reactance of fundamental frequency**
   - **For** $h = 1$: $X_{h(1)} = \left[ h^2 - (h^2 - 1) \right] X_{\text{eff}}$ (3)
   - **For** $h = 2$: $X_{h(2)} = X_{h(1)}$ (4)
   - **Where:** $h =$ harmonic order tuned by filter with safety factor

10. **Item 6. Determine rms filter current**
    - **Fundamental current on filter connected to:**
      - **For** $h = 1$: $I_{h(1)} = V_{\text{LN}} / \left[ X_{h(1)} - X_{h(1)} \right]$ (5)
      - **Fundamental Current in filter which Connected in Y - Series:**
      - **For** $h = 1$: $I_{h(1)} = I_{h(1)}$ (6)
    - **For** $h = 2$: $I_{h(2)} = I_{h(1)}$ (7)

11. **Alternative circuit to calculate current harmonic of filter based on IEEE Std 1531-2003 is shown in Figure 2.**

**Figure 1. Steps to determine the capacity of harmonic filters with single-tuned filters for 20 kV & bus 0.4 kV**

The steps are as follows:

1. **Step 1. Determine the level of short-circuit current in customers**
   - **Assess the contribution of customers injected current and voltage harmonic into the system following the steps as follows:**
     1. **Determine the capacity of short circuit in the system (MVA\(_{SC}\)).**
     2. **Determine base impedance (Z\(_{base}\)).**
     3. **Determine base current (I\(_{base}\)).**
     4. **Determine source impedance (Z\(_{source}\)).**
     5. **Determine power transformer (Z\(_{Trafo}\)) and customer transformer (Z\(_{Trafo,\text{Cust}}\)) impedance.**
     6. **Determine Line 20 kV impedance (Z\(_{line,20\,kV}\)).**
     7. **Determine short circuit current in costumer (I\(_{sc,20\,kV}\), I\(_{sc,0.4\,kV}\)).**
     8. **Determine installed load Customer (I\(_L\)).**
     9. **Determine ratio (I\(_{sc,20\,kV}/I_L\)) or (I\(_{sc,0.4\,kV}/I_L\)).**

2. **Step 2. Determine the level of the individual current and voltage harmonic of field measurements higher than IEEE standard 519-1992**
   - **Currents and voltage harmonics values of each harmonics order compared with IEEE Standard 519-1992 and then made evaluation-order harmonics which are higher than the standard.**

3. **Step 3. Determine the level of the individual current and voltage harmonic**
   - **After Flow highest-order harmonic is determined, then do the design of the filter.**

4. **Step 4. Determine the Filter Design**
   - **Item 1. Determine the initial power factor (pf\(_I\)) and power factor (pf\(_I\)) of the target customers**

   - **Item 2. Determine the effective capacity of reactive power filter** $Q_{\text{eff}} = S \times \left[ \sin(\cos^{-1}p_f) - \sin(\cos^{-1}p_f) \right]$ (1)
     - **Where:** $S =$ Customer Install Capacity

   - **Item 3. Determine the frequency tuning filters**
     - **In accordance with IEEE 1531-1993, harmonic single-tuned filter frequency is determined in amount of 3%-15% below the determined frequency as safety factor.**

   - **Item 4. Determine impedance of effective filter**
     - **X_{\text{eff}} = \left( V_{\text{LL}} \right)^2 / Q_{\text{eff}}$ (2)

   - **Item 5. Determine capacitive and inductive reactance of fundamental frequency**
     - **For** $h = 1$: $X_{h(1)} = \left[ h^2 - (h^2 - 1) \right] X_{\text{eff}}$ (3)
     - **For** $h = 2$: $X_{h(2)} = X_{h(1)}$ (4)
     - **Where:** $h =$ harmonic order tuned by filter with safety factor

   - **Item 6. Determine rms filter current**
     - **Fundamental current on filter connected to:**
       - **For** $h = 1$: $I_{h(1)} = V_{\text{LN}} / \left[ X_{h(1)} - X_{h(1)} \right]$ (5)
     - **Fundamental Current in filter which Connected in Y - Series:**
       - **For** $h = 1$: $I_{h(1)} = I_{h(1)}$ (6)
       - **For** $h = 2$: $I_{h(2)} = I_{h(1)}$ (7)

   - **Alternative circuit to calculate current harmonic of filter based on IEEE Std 1531-2003 is shown in Figure 2.**

   **Figure 2. Substitute circuit Harmonic Flow Fundamental to the Filter**
Item 7. Determine capacitive and inductive reactance of harmonic frequency
\[ X_{L(h)} = h X_{C(1)} \] .................................(9)
\[ X_{C(h)} = X_{C(1)}/h \] .................................(10)
\[ R_{HS20kV(h)} = R_{HS20kV(1)} \] .................................(11)
\[ X_{HS20kV(h)} = h X_{HS20kV(1)} \] .................................(12)
\[ Z_{HS20kV(h)} = \sqrt{((R_{HS20kV(h)})+ (X_{HS20kV(h)})^2)} \] .................................(13)

![Figure 3. Alternative circuit of current harmonic h\textsuperscript{th} order with filter in bus 20 kV](image)

Item 8. Determine rms filter current
Harmonic current on filter connected to:
\[ I_{(h)} = V_s/[X_{C(1)} - X_{L(1)}] \] .................................(14)
Fundamental Current in filter which Connected in Y- Series.
\[ I_{(h)} = (Z_{HS20kV(h)})((X_{L(1)} - X_{C(1)}) x I_0) \] .................................(15)
\[ I_{th} = I_0 - I_{(h)} \] .................................(16)
\[ I_{th}/I_0 \] .................................(17)

Where : h = harmonic order

The results obtained from equation (17) and compared with the standard IEEE 519-1992.
If the result is less than the standard, then the calculation can proceed to the next step.
If the result is greater than the standard, then the calculation back to step 4.

Item 9. Determine rating of reactive power capacity of capacitor
\[ Q_{Crated} = (V_{LL})^2/X_{C(1)} \] .................................(18)

Item 10. Determine current of nominal capacitor
Current of nominal capacitor
\[ I_{Nom} = Q_{Crated}/\sqrt{3} V_{ll} \] .................................(19)

CASE STUDY

The objects being studied are the end users with 20 kV arc furnaces with power of 3,465 kVA which is supplied from main station 150/20 kV Sei Rotan with capacity of voltage regulator in amount of 31.5 MVA.

Data were obtained:
- MVA short circuit Level = 5,334.71 MVA
- Installed capacity Sei Rotan substation = 31.5 MVA
- Transformer Primery voltage = 150 kV
- Transformer Secondary voltage = 20 kV
- Power transformer Impedance = 11%
- Customer transformer Impedance = 4%
- Line 20 kV Impedance = 0.235 + j0.061 \Omega
- Installed capacity costumer = 3,465 KVA
- Operation voltage = 20 kV

To determine the ratio \( I_{20kV}/I_{L} \) and determine the single tuned filter design can use a simple circuit as shown in figure 5.

![Figure 5. One short circuit diagram with 3 phases in bus 20 kV/0.4 kV and Filter installation](image)

Results of Analysis obtained:
- \( Z_{Base} = (KV_{Base})/\sqrt{3} \)
- \( I_{Base} = KV_{Base} / (\sqrt{3} x KV_{Base}) = 909.33 \) Amper
- \( Z_{source} = ((KV_{Base})^2 / MAV_{Asc})/Z_{Base} = j0.00599 \) pu
- \( Z_{Trafo} = j0.11 \) pu
- \( Z_{line 20 kV} = 0.235 + j0.061 \Omega = 0.1815 + j0.00484 \) pu
- \( I_{20kV} = KV_{Base} / (Z_{source} + Z_{Trafo} + Z_{line 20 kV}) \)
- \( I_{20kV} = 8.19 \) pu
- \( I_{20kV} = 7,446 \) Amper
- \( I_L = MAV_{Asc} / (\sqrt{3} x KV) = 100.03 \) Amper
- \( I_{20kV}/I_L = 7,446 / 100.03 \) = 74.44 kali

With a ratio of 74.44 times (51 to 100 times) and voltage of 20 kV (< 69 kV) service can be specified limit voltage and current harmonic distortion in accordance with the IEEE 519-1992 standard, as follows:

<table>
<thead>
<tr>
<th>Voltage Distribution Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Voltage</td>
</tr>
<tr>
<td>&lt; 69 kV</td>
</tr>
<tr>
<td>&gt;69 kV and &lt;161 kV</td>
</tr>
<tr>
<td>&gt;161 kV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current Distortion Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Harmonic Current Distortion in Percent of I_s</td>
</tr>
<tr>
<td>harmonic number (i)</td>
</tr>
<tr>
<td>L_20</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 1. Harmonic Distortion IEEE Standard 519-1992
The measurement of voltage and current harmonics in the field on March 9, obtained as follows:
- Harmonic spectrum of voltage order
- Harmonic spectrum of current order

The results of the field harmonic measurements compared to standard IEEE 519-1992. For voltage, total harmonic distortion (THD_v) still qualify (< 5%). For current, harmonics to 5th, 11th and 23rd order beyond the Standard IEEE 519-1992.

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Value</th>
<th>Harmonic 5th Order</th>
<th>Harmonic 11th Order</th>
<th>Harmonic 23th Order</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th</td>
<td>10.0</td>
<td>10.0</td>
<td>14.03</td>
<td>beyond the standard</td>
<td></td>
</tr>
<tr>
<td>11th</td>
<td>4.5</td>
<td>4.5</td>
<td>5.48</td>
<td>beyond the standard</td>
<td></td>
</tr>
<tr>
<td>23rd</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>beyond the standard</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Comparison IHD on March 9 and Standard of IEEE 519-1992

The next step is to create a single filter design tuned order 5 (the largest harmonic currents).

**DETERMINING HARMONIC FILTER CAPACITY WITH FILTER 5th ORDER IN BUS 20 kV**

1. Determine power factor (pf_0) and the targeted Power Factor (pf_i) from arc furnaces charge.
   - Maximum active power (average) = 464.238 kW.
   - Maximum reactive power (average) = 278.893 kVar.
   - Maximum apparent power (average) = 541.570 kVA
   - Early power factor (pf_0) = cos 31.01° = 0.857 lagging
   - Targeted power factor (pf_i) = 0.95 lagging
   - Customer Install Capacity = 3,465 kVA

2. Determine effective power capacity of filter reactive.
   \[ Q_{\text{eff}} = S \times [\sin (\cos^{-1} pf_0) - \sin (\cos^{-1} pf_i)] \]
   \[ = 3,465 \times [\sin (\cos^{-1} 0.857) - \sin (\cos^{-1} 0.95)] \]
   \[ = 702.43 \text{ kVAR} \]

3. Determine tuning filter frequency
   In this case, use tuning filter frequency of 5.6% (4.72).

4. Determine impedance of effective filter
   \[ X_{\text{eff}} = V_{\text{LL}}^2 / Q_{\text{eff}} \]
   \[ = (20\sqrt{2}) \times 1000 / 702.43 = 569.45 \Omega \]

5. Determine capacitive and inductive reactance of fundamental frequency
   \[ X_{C(1)} = h_1 / (h_1^2 - 1) \] \[ X_{L(1)} = h_1^2 \]
   \[ X_{\text{eff}} = 569.45 / 26.76 = 26.76 \Omega \]

6. Determine rms filter current
   Fundamental Current in filter which Connected in Y-Series
   \[ I_{h(1)} = (20,000/\sqrt{3}) / (596.21–26.76) = 20.28 \text{ A} \]
   \[ I_1 = 100.03 / 20.28 = 79.75 \text{ A} \]
   \[ I_1/ I_h = 79.75 / 100.03 = 79.73 \% \]

Alternative circuit to calculate current harmonic of filter based on IEEE Std 1531-2003 is shown in Figure 8.

**Figure 8. Substitute circuit Harmonic Flow Fundamental to the Filter**

Current of 5th order of filter:
   \[ X_{L(5)} = 5 X_{L(1)} = 5 \times 26.76 = 133.81 \Omega \]
   \[ X_{C(5)} = X_{C(1)}/ 5 = 596.21 / 5 = 119.24 \Omega \]
   \[ X_{R_{B(20kV)(5)}} = 5 X_{R_{B(20kV)(1)}} = 5 \times 1.533 = 7.665 \Omega \]
   \[ R_{B(20kV)(5)} = R_{B(20kV)(1)} = 0.235 \Omega \]
   \[ I_{5} = 3.465 \text{ kVA} /\sqrt{3} x 20 \text{ kV} = 100.03 \text{ A} \]
   \[ I_5 = 0.1402 x 100.03 = 14.02 \text{ A} \]

Alternative circuit to calculate current harmonic of 5th order is shown in figure 9 as follows:

**Figure 9. Alternative circuit of current harmonic 5th order with filter in bus 20 kV**
By changing the power factor of individual load, the harmonic current can be reduced by 34.5%. From the aforementioned discussion, it can be concluded that:

1. By changing the power factor of 0.86 to 0.95, Individual Harmonic Distortion (IHD) Current 5th order can be reduced by 34.5%, from 14.02% (not in accordance with IEEE 519-1992 standards) to 9.18% (in accordance with IEEE 519-1992 standards). Likewise with Total Harmonic Distortion (THD).
2. Filter capacity needed to compensate harmonic 5th order of electricity supplier (20 kV) is: Capacity Reactive Power of 670.9 kVAR, Nominal Current of 19.37 A, Inductive Reactance of 26.76 Ohm or Inductance of 85.23 mH (mili Henry), Capacitive Reactance of 596.21 Ohm or Capacitance of 5.3 µF (micro Farad).

From the conclusion, the suggestion might be given as follows:

1. The end users injecting current harmonic or voltage exceed the standard IEEE 519-1992 or the provision determined by the electricity company provider are obligated to install harmonic filter.
2. Implementing penalty tariff to the end users of arc furnaces or some kind of exceeding the standard IEEE 519-1992 or the provision determined by the electricity company provider.

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