How much measurement error can someone expect from various degrees of CT saturation?

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Abstract—

Current transformer saturation is normal occurrence in the field. The system often has been reconfigured or strengthened since the current transformer was put into place. This often results in higher available fault current, which can lead to CT saturation during faults. Usually, the degree of saturation due to AC and DC fault current is not enough to cause the system to misoperate, but is enough to introduce measurement error to the relay. Other times, it causes the relaying to trip/malfunction. Replacing CTs that occasionally saturate during faults often times is impractical and unnecessary.

Keywords— current transformer, relaying, transformer saturation

I. Introduction to Current Transformer Saturation

What is a current transformer (CT)? A current transformer is a series transformer that steps down the currents on the primary side and feeds them to devices connected on the secondary side. The stepped downed currents are then used by devices like relays and meters. Additionally, the CT isolates the primary high voltage side from the secondary side so that the secondary equipment doesn't need to be insulated to primary voltages. A current transformer is an intermediary between the currents on the grid and measuring and control devices.

Assuming an ideal transformer model, the voltages and currents on the primary and secondary sides are related exactly by the turn ratios. Vprimary/Vsecondary = Isecondary/Iprimary = (# primary winding turns)/ (# secondary winding turns). The ideal model of a current transformer is a good approximation when the transformer is not near saturation or low excitation.

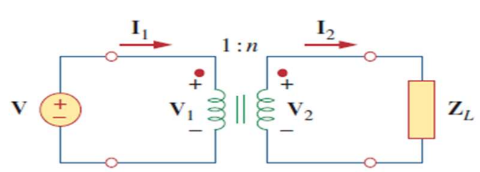

Fig. 1 . Ideal transformer without winding impedance or magnetizing branch.

The ideal transformer model doesn't consider the winding impedance nor the magnetizing branch of the transformer model. The magnetizing branch is the portion responsible for non-linearities during saturation.

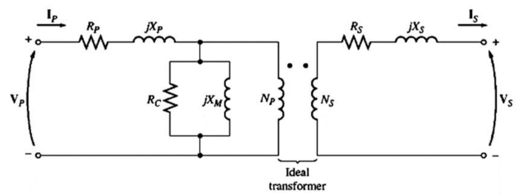

Fig. 2. Transformer model with winding impedances and core loss and magnetizing branch

The portion of the transformer T-model that causes error in current measurements is the excitation branch with parallel impedance's Rc and Xm. [Fig. 2] The current that passes through the impedance Rc and accounts for the core losses and eddy current effects. The current which passes through Xm is the magnetizing current. The impedance Xm is non-linear and responsible for the effects of saturation.

The current that passes through the excitation branch is sometimes called error current since it causes the primary current, Ip, to no longer be a multiple of the secondary current, Is. When a CT saturates, the value for the non-linear impedance Xm decreases to the point that a significant and potentially affecting amount of excitation or error current results. A saturated transformer can be looked at as two separate circuits, which are no longer or not strongly coupled. This can be seen when a current transformer saturates and the current on the secondary shows LR exponential current decay when the burden is very inductive.

The CT performance is often given with a graph with the secondary voltage on the Y-axis and the secondary excitation current on the X-axis.[Fig 3.] The graph is used as a basis for sizing CTs [CT protective standard and modern world]. The parallel lines represent the CTs performance at different taps. The CT has the highest knee-point when using full taps and is de-rated proportionally when lower taps are used. For example, a 2000:5 C800 tamped down to 1000:5 will have a knee-point secondary voltage half of that at full scale.

There are two separate definitions for the knee-point of the excitation curve. The first definition defines it as the point where a 10% increase in voltage results in a 50% increase in excitation current. . The second definition defines it as the point on the curve with a 45-degree slope. However the knee-point is defined, it conceptually is the point where the transformer is no longer linear.

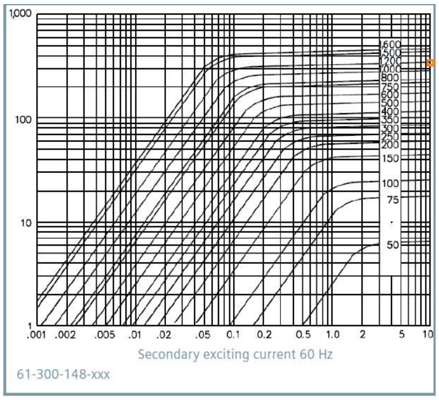

Fig. 3. Excitation curves for a Siemens CT

The excitation curve and the B-H plot provide insight into CT saturation or core hysteresis, but the the key concept is a transformer with a volt-second rating. A volt-second rating is when a transformer can only tolerate being driven in one magnetic polarization for so long before all the domains line up and all saturation is due to voltage and not current. The volt-sec is the integral of the voltage waveform. [Fig. 5] Power transformers can be modeled with the same T-model and will often generate harmonic when overexcited above 1.05-1.1 pu unit voltage. The difference is the grid voltage is saturating the core in the case with a power transformer. The current is driven through secondary winding impedance, cabling, and any connected devices creates the voltage seen by the excitation branch of a current transformer. Same concept but derived from two separate quantities.

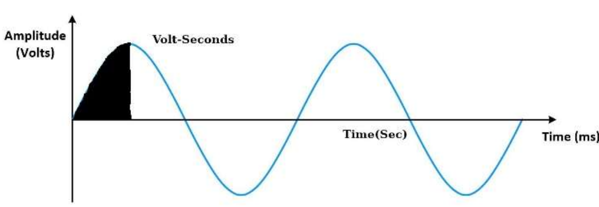

Fig. 5. Diagram showing the volt-second integral.

This volt-second concept simplifies the explanations for the following characteristics that can contribute to CT saturation:

The second plot that is often shown when explaining CT saturation is the hysteresis B-H curve. [Fig.4] B represents the magnetic flux density and H is the applied field. This while not very useful for any sort CT saturation or sizing calculation does provide a visual basis for saturation, remanence and how different core materials compare.

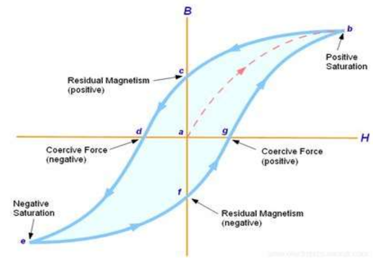

Fig. 4. B-H Magnetic Hysteresis Loop

1. DC bias - DC is biased in one polarity. The volt-second integral continues to increase until it hits the volt-second rating of the core. DC usually results in the waveform looking asymmetrical. Inductive burdens tend to reduce the amount of saturation seen by DC or quasi DC currents due to their impedance being frequency dependent. Zl = j*w*l. The DC offset also decays with the –L/R time constant.

2. AC saturation - AC saturation due to high symmetrical currents is the result of the volt-second rating of the transformer being exceeded before the polarity of the AC sine wave changes. The integral over one period of a sine wave equals zero, so saturation has to occur in each half cycle before the polarity flips. AC saturation tends to look like symmetrical shark fins.

3. Remanence – residual magnetization left in the core iron will look like DC bias and produces an asymmetrical waveform. Remanence can't last long like DC bias since DC bias is the result of decaying energy in grid inductance.

4. Excessive burden – burden that is large enough to cause saturation will look similar to saturation caused by excessive AC current. There is no difference between excessive excitation caused by a large amount of current passing through a small burden or small amount of current passing over a large burden.

II. PROTECTIVE RELAYING

Protective relays are used to isolate problems on the grid, such as electrical faults, and reconfigure the system to protect people and equipment. These devices typically are fed stepped down voltages and currents, which are used by the relay to determine what to do.

There are three different eras of protective relaying: mechanical, solid state, and microprocessor based.

Mechanical relays are the oldest. It is not for a well-maintained mechanical relay to be in service for over 40 years. The devices consisted of spinning disk, plungers, resistors, inductors, capacitors, and transformers. They often are still in service but are being phased out due to age and an inability to find replace parts. It is not unusual to hear stories of utilities scouring Ebay for used parts. The number of protective functions housed in a relay is one or two elements.

Solid state relays were the next generation of protective relays. With this generation, the move parts like spinning disk, springs, and plungers needed by the previous generation, were replaced with electronics. These relays sometimes included a microcontroller but lacked many of the common features of the next generation of relays. Each device are only capable of supplying a few protective functions.

Microprocessor relays are the last generation of relays. As the name suggest, they have a microprocessor and are programmable. This allows for a tremendous amount of flexibility. Since the relays have a microprocessor, they are able to carry out complex math operations and provide a large number of protective elements. An entire relay panel of mechanical relays can be replaced)by one or two microprocessor relays.

These three generations of devices are inherently very different even if they are providing the "same" functions. For the purpose of this paper, the responses Peak, True RMS, and One-Cycle Cosine Filtered will be examined to see its response to various degree of CT saturation. There are relays that average the current signal over a window or microprocessor that have proprietary algorithms to mitigate issues related to CT saturation. Microprocessor relay manufacturers that employ proprietary tricks help mitigate the effects of CT saturation. One paper remarked in its evaluation of CTs that in relays that have countermeasures to CT saturation countermeasures the maximum value of the current needing to be measured accurately needs to 2/3rds the current saturation limit of the CT. [2] Responses of mechanical relays widely vary and need to be tested to determine their response to harmonics. [1] This paper is about examining some come measurement methods and developing a means to quickly estimate potential error.

A. Types of relay responses

1. Instantaneous Peak - this is the simplest response a relay can have and is or was often used for instantaneous elements. If the current crosses the set point, the relay operates without delay for calculations. The downside is the setpoint needs to be coordinated to not operate due to DC inrush and harmonics or spikes. This is due to no filtering. The peak was set by looking back one cycle and determining the maximum absolute value.

2. True RMS - this response involves calculating the root mean square of the current without any filtering. All harmonics and DC offset are allowed to contribute to the True RMS calculation. The benefit of this is that fuses and equipment heat and coordinate with True RMS. [5] The force in due to flux in flux based devices is proportional to the integral of the square of the current. [7]

$$x_{\text{RMS}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}$$

Eq. 1

3. One-Cycle Cosine Filter - this filter provides a good transient response and filters out decaying DC and harmonics. It is very similar to a DFT for the frequency that you interested in. The Cosine filter takes advantage of the fact according to Euler's identity, rotating the cosine 90 degrees gives you the sine. This allows a 90 degree lag in the cosine coefficients to be used in place of the sine coefficients. It reduces the computational burden of calculation.[3] [4] The cosine filter also provides a slightly better response to DC offset than the single frequency DFT. When coordination of with fuses or there is equipment that needs to be protected from harmonics,filtering out everything but the fundamental component could be an issue. An upside is that you don't need to include margin in your pickups for DC offset. The equations for how this filter is put together is in Appendix B. Generally, microprocessor relays will not be significantly affected with harmonic levels below 20%. [1]

III. RELAY RESPONSE TO SATURATION

One common problem is the difficulty in determining the impact of a slightly saturated current waveform on the instantaneous peak, True RMS, and One Cycle Cosine Filter without carrying out a simulation. Usually there is not enough time to carry out a simulation to determine if the impacts of CT saturation are unacceptable -- unless there was a misoperation. There needs to be a methodology to get an estimate of the impact that various degrees of saturation has on current measurements. The goal of this paper was to create a method that helped in making rough estimates as to how much error was present in a saturating CT measurement. Since saturating waveforms are complex, it was difficult to come up with a simple rule of thumb that could quickly be used to ballpark the amount of error for different calculations. Ultimately, a lookup table was created.

CT performance data was gathered using the PSRC CT saturation calculator. This provided data that was used to compare the ideal performance of Peak, True RMS, and One-Cycle Cosine Filter responses to a saturating one cycle waveform. The PSRC CT saturation calculator comes with a DFT filter. Performance-wise, the DFT filter performs similarly to the One Cycle Cosine Filter but requires more calculation and has slightly poorer DC response. This modified spread sheet provided a benchmark as to how much the calculations deviated with various amounts of saturation.

The goal wasn't to validate the usefulness of any of the calculations. For example, Peak and True RMS calculations would vary with the DC offset and likely would be set with additional margin that wouldn't be needed with the One-Cycle Cosine Filter due to it being able to filter out the DC component supplied when the CT wasn't saturating.

The different degrees and shapes of the saturated waveforms were created by adjusting the burden resistances and the DC offset. This allowed various offset waveforms with differing amounts and types of saturation to be created.

The one cycle that was used in the calculations was the second cycle or 16.66 ms after the fault. The X/R ratio was set to 40, which means that the DC time constant was around 100 ms or 8 cycles. The calculations for the True RMS and peak calculations were applied to a waveform with a slow decaying DC offset. The cosine filter would be able to filter out the DC component when the CT wasn't saturating, although it would still be affected by the DC component saturating the CT

IV. Relay response to saturation

The results from the waveforms and the error for Peak, True RMS, and One-Cycle Cosine Filter are found in Appendix C.

Appendix C was put together as a reference for how much error can be expected with saturated waveforms of different shapes from the ideal case with that measurement method. This is not meant to be a hard calculation of error but something that can be referenced by an engineer to give a rough idea of how much error he or she might have in his measurement. There is a lot of effort by people to create methods to properly size CT to avoid saturation or algorithms that can be used forensically to try to remove the impacts of saturation. There isn't much effort to make it easy to review how much error a saturating CT might create without doing a full-blown calculation.

The problem with CT saturation is it can produce many different waveforms in response to the same symmetrical currents. Each being different depending on the burden, power factor of the burden, phase of the fault on the waveform, the amount of DC offset, remanence, and the amount of current.

This is also further complicated because AC and DC saturation are not independent of each other. A CT core that is biased with DC often will show clipping on the biased side from the volt-second characteristic of the CT being exceeded by the sum effects of the AC and DC saturation. The problem is it is difficult to derive good rules of thumb since there are two different effects working in tandem that produce can produce a variety of waveforms. AC saturation by itself will often produce waveforms which resemble symmetrical shark fins. If this was just the case, it might be possible to simply measure the gap between the shark fins to derive some type of estimate of how much error is present. With DC, asymmetry is introduced. The wave forms in Appendix C are sorted by groupings of the same resistive burden and then with increasing amounts of DC offset. This is why using Appendix C to find a like waveform is likely the simplest and quest solution to quickly estimating measurement error.

Here are a few comments about using Appendix CB to estimate error:

- Compare one cycle that you are examining to a sine wave that lines up with as much as possible with your saturated waveform. Waveforms with heavy DC bias will often have one half of the waveform that doesn't saturate. This helps in estimating what the ideal waveform may have looked like. For waveforms with heavy AC saturation, the front half of the shark fins provide reference as to how the ideal waveform should line up. The regions where the CT is operating linearly provide reference points for what the ideal waveform should look like. This is assuming that the DC offset is decaying slowly and the symmetrical current are both not changing greatly during the one cycle period.

- Compare when on a waveform the saturation starts occurring. The error Peak measurement will give you a good idea of how where on the waveform it started to saturate. If a waveform in Appendix C list shows a 5%

Peak error, it will indicate where exactly the shark fin started clipping and can be used as a point of reference to the waveform that you are examining.

- Look to see how offset your one cycle waveform is. If your waveform peaks are 1 p.u. positive and 0.5 p.u. Negative, you should compare it to waveforms in the appendix that are similarly offset. True RMS and Peak calculations are greatly affected by DC offset.

- Pay close attention to the shape of the waveform when it saturates. This plays a much larger role than expected in determining how much error the True RMS and Cosine Filters will have. A gradual decline from the saturating point to the waveforms zero crossing will give a very different amount of error than if the waveform drops initially to near zero and then glides to the next zero crossing.

-Try, if possible, to adjust your scales similarly to the waveforms in Appendix C. This will make the comparison a little easier.

- The general amount of error in the cosine filter result will be similar to the percentage of the AC portion of the waveform that was lost to saturation. If your waveform was clipping around 25% of the positive and negative half cycles due to AC saturation, you will have around 25% error.

- The True RMS calculation is biased heavily to producing a lot of error if the saturation starts clipping the peak of the waveform. This is due to the square term in RMS calculation.

- Many of the relay manufactures have propriety algorithms that help the devices operate correctly when they detect CT saturation. While Appendix C provides some insight into how much error might exist with saturation, the ultimate proof in the pudding from a relaying point of view is "did the device operate correctly?" There are even protective relaying schemes like high impedance bus differential which take advantage of CT saturation to safeguard them from tripping for out of zone faults.

- Remanence was not modeled in creating these waveforms. However, the waveforms in Appendix C are ultimately a comparison between measurements with ideal and non-ideal waveforms. The source of the distortion doesn't matter. The PSRC Saturation Calculation tool was only used because it models CT saturation. The waveforms it generates will be common to saturating CTs. Also, remanence itself is a relatively short-lived phenomena. While remanence is like bias that is caused by DC offset, DC offset is the result of the system configuration changing and energy being discharged from the grid's inductance. The DC offset is the result of this energy decaying with the time constant of L/R or (X/R)/(ω). This offset actively tries to bias the CT core until it has dissipated. Remanence has no underlining phenomena that continues trying to bias the core.

IV. Conclusion

A table of different waveforms can be used to help estimate the amount of error in a saturated waveform. The physics of CT saturation are impartial to this except that saturated waveforms have common characteristics and form a family waveforms. The intent of Appendix C was to layout a many waveforms that could be used for reference since they are similar to one-cycle waveforms during saturation. Only one cycle was reviewed because it is short enough to limit the impact of decaying DC offset and changing symmetrical fault current due to any number of things like an evolving fault or a transition from sub-transient to transient reactance in generators. At the same time, one cycle is long enough to show asymmetry due to DC bias or remanence.

This didn't model all the algorithms that are used to estimate the amount of error present during saturated CT measurements. It is shown ,however, how a lookup table of distorted waveforms can be used to give an engineer a rough idea of the amount of error present without having to resort to a full blown study.

The waveforms and harmonics created by CT saturation start getting into the concept of relay performance due to poor power quality, which wasn't really touched upon in this paper but is clearly related.

This entire concept of only looking at one cycle to estimate error could easily be extended without needing to have data related to CT performance curves, taps, or burdens. It is just focusing on how much does the output deviate from the assumption that I should be seeing something very similar to an offset sine wave. Oscillography programs could incorporate it with the disclaimer that it won't be accurate under hard and fast transitions. A quick and dirty method to estimating error would be helpful because often engineers have nothing due to not having enough time to do a full blown evaluation.

Douglas Millner holds a B.S. and M.S. in Electrical Engineering from the University of Minnesota - Twin Cities and Michigan Technological University. He has been a 15 year member of IEEE Power and Engineering Society. He has 15 years of experience across I&E design, protective relaying, NERC compliance, and transmission planning with consulting companies, manufactures, and utilities. He has a particular interest in power system studies and protective relaying. Currently, he is working on building up his own engineering consulting firm, NERX Power Consultants LLC.

Iς. References

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[6] "IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes," in *IEEE Std C37.110-2007 (Revision of Std C37.110-1996)* , vol., no., pp.1-90, 7 April 2008, doi: 10.1109/IEEESTD.2008.4483716.c

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Appendix A – PSRC CT Saturation Calculator – Input Parameters

INPUT PARAMETERS:		ENTER:	
Inverse of sat. curve slope =	S =	22	---
RMS voltage at 10A exc. current =	Vs =	400	volts rms
Turns ratio = n2/1=	N =	240	---
Winding resistance =	Rw =	0.000	ohms
Burden resistance =	Rb =	2	ohms
Burden reactance =	Xb =	2.000	ohms
System X/R ratio =	XoverR =	40.0	---
Per unit offset in primary current =	Off =	1.00	-1<Off<1
Per unit remanence (based on Vs) =	λrem	0.00	---
Symmetrical primary fault current =	Ip =	12,000	amps rms

Appendix B. – Cosine Filter

$$\text{Filter Coefficients} = CFC_n = cos(2 * pi/(samplerate))$$

$$\text{Cosine Filter} = IX_{smpl+spc} = 2/(N+1) * \sum_{n=0}^{N} I_{smpl+spc-n} * CFC_n$$

$$\text{The Phasor Magnitude} = |I_o| = \sqrt{(IX_{smpl+spc})^2 + (IX_{smpl+spc-spc/4})^2}$$

$$\text{N} = \text{samples}$$

$$\text{n} = 0,1 \ldots \text{N}$$

$$\text{smpl} = \text{sequence of samples } 0,1,2,3\ldots$$

$$I_{smpl+spc-n} = CurrentSamples$$

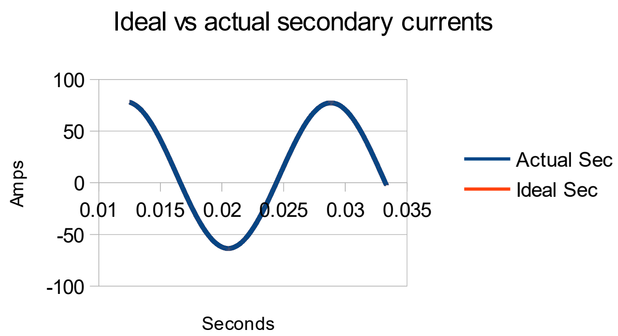
$$IX_{smpl+spc} = FilterOutput$$

References : [3] [4]

Appendix C. Saturated Waveforms with error in Peak, True RMS, and One-Cycle Cosine Filters

1ohm

1



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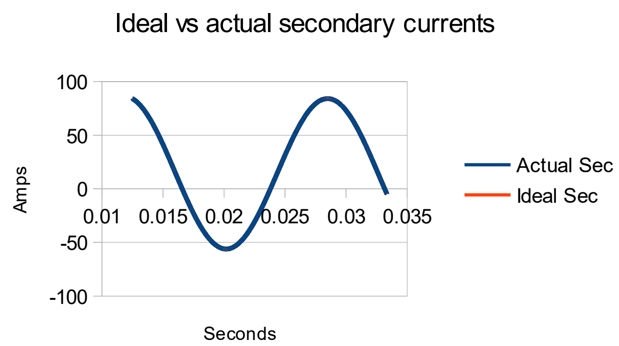

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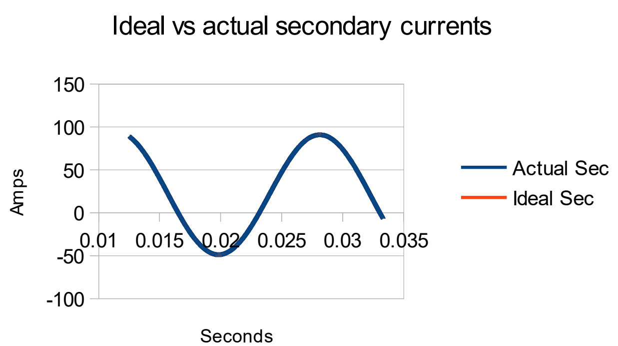

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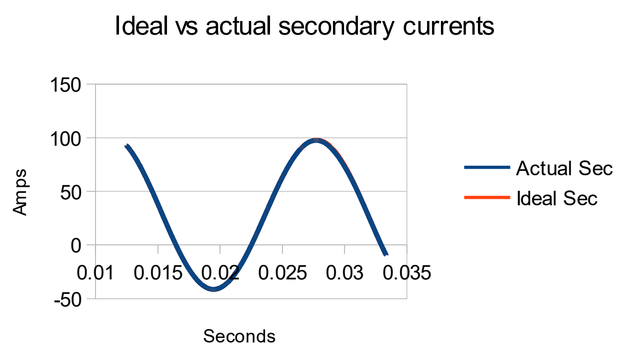
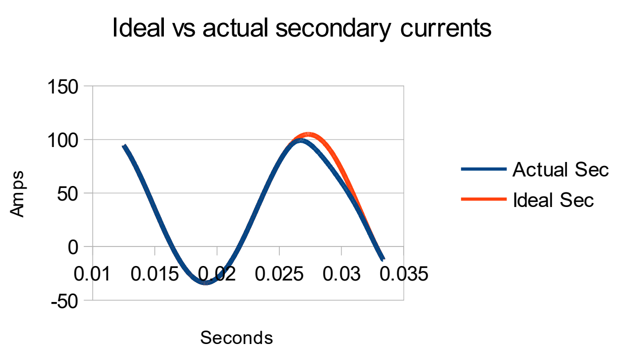


Case	1	2	3	4
True RMS Error	0%	0%	0%	0%
Filtered Fundamental Error	0%	0%	0%	0%
Peak Error	0%	0%	0%	0%

5



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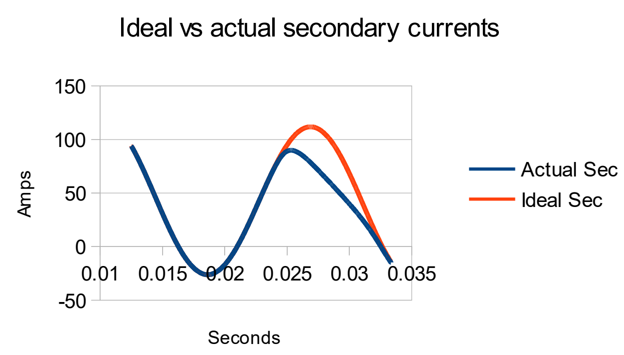

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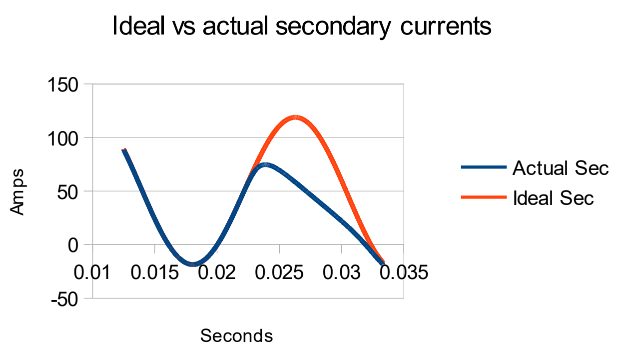

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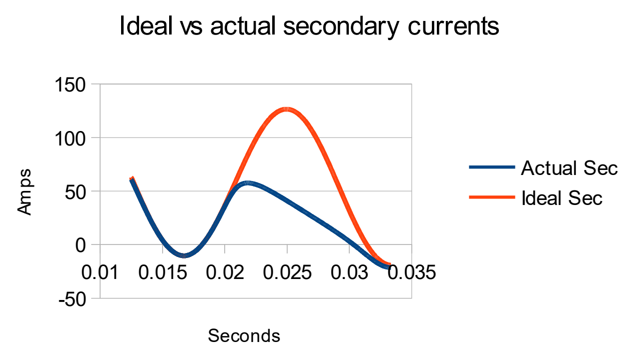
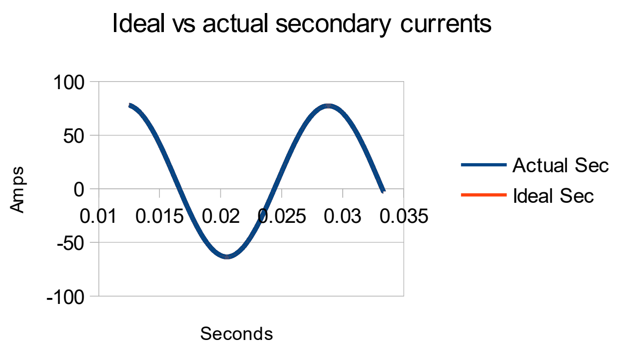


Case	5	6	7	8
True RMS Error	7%	23%	41%	57%
Filtered Fundamental Error	4%	16%	35%	58%
Peak Error	5%	20%	37%	54%

9



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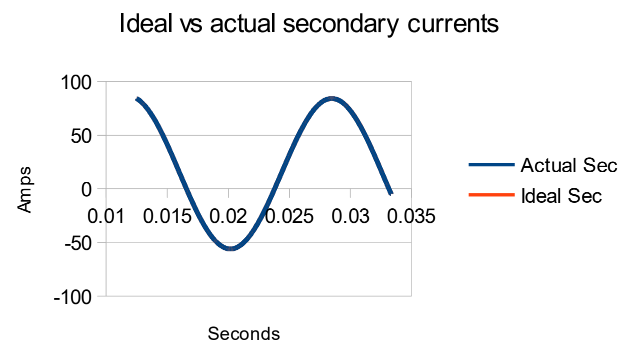

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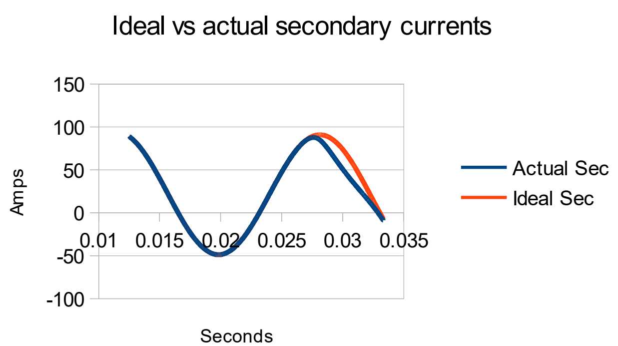

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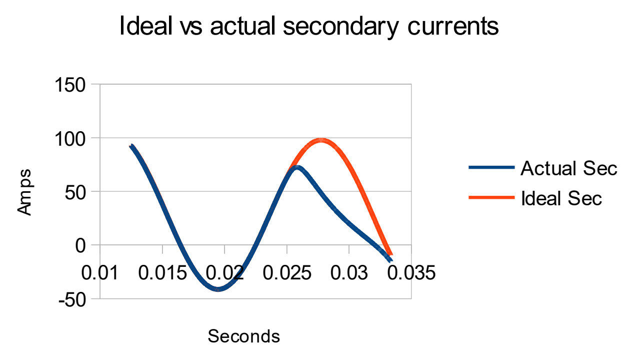
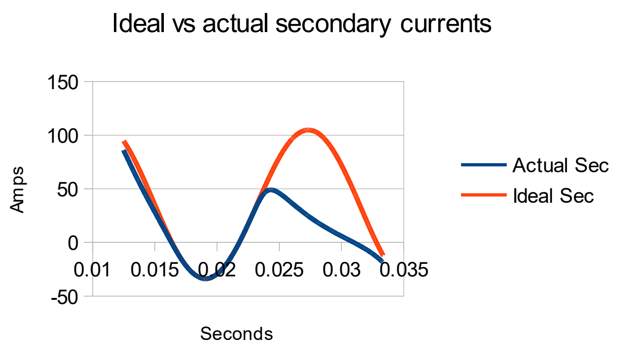


Case	9	10	11	12
True RMS Error	0%	0%	9%	34%
Filtered Fundamental Error	0%	0%	0%	15%
Peak Error	0%	0%	3%	26%

13



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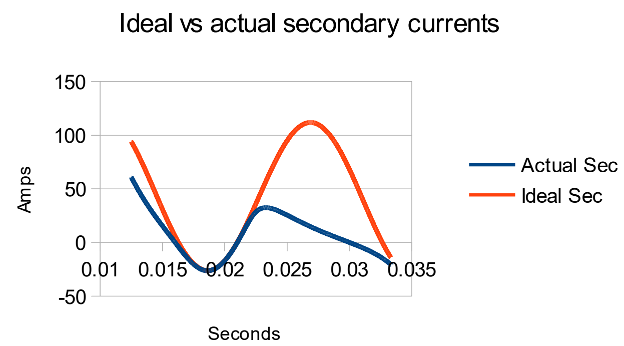

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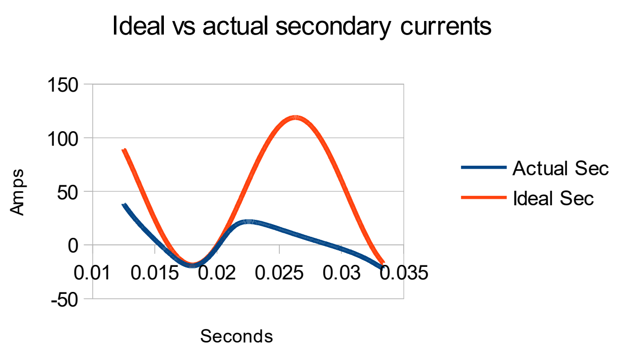

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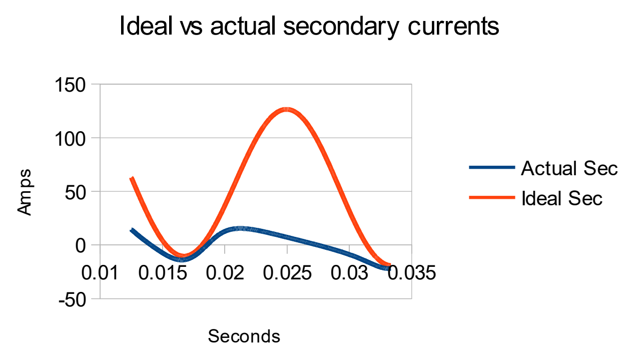
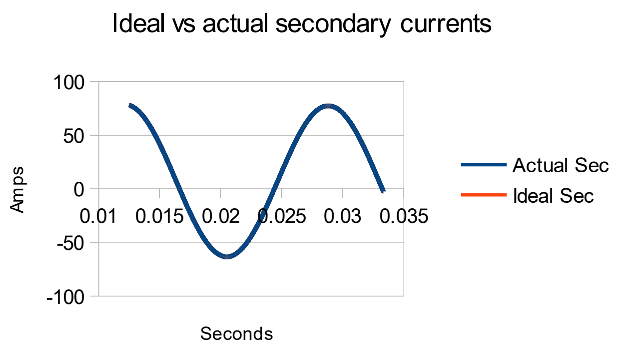


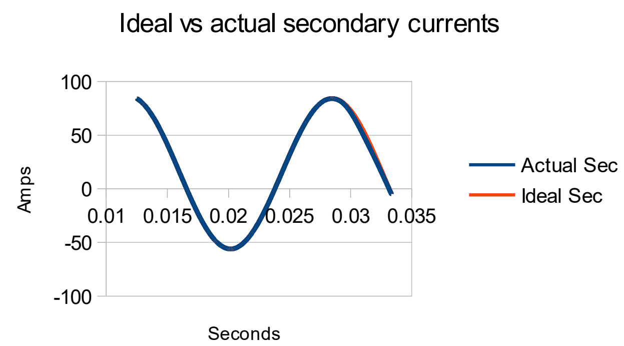
Case	13	14	15	16
True RMS Error	57%	71%	80%	85%
Filtered Fundamental Error	40%	61%	74%	82%
Peak Error	53%	71%	82%	83%

2-5ohm

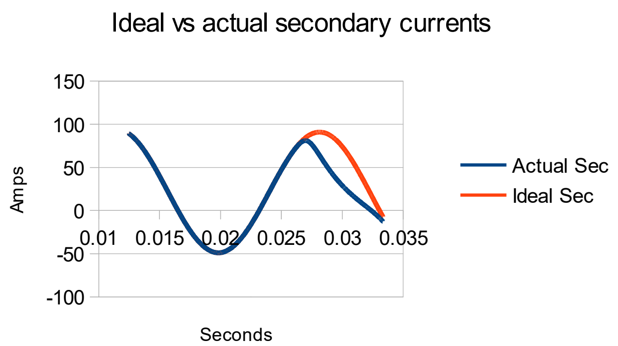
17



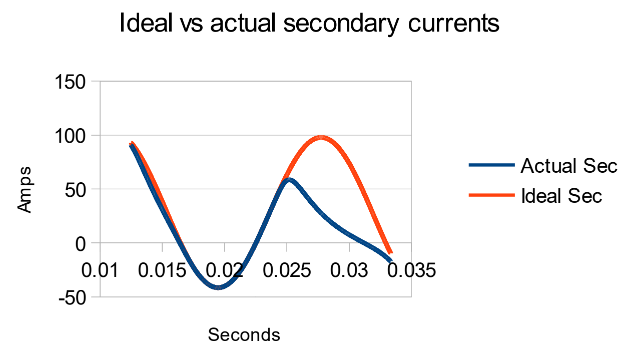
18



19

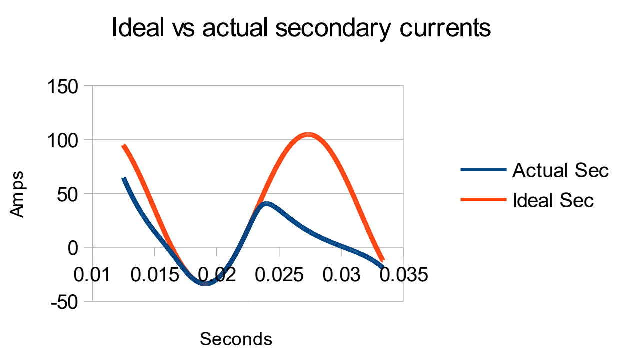


20

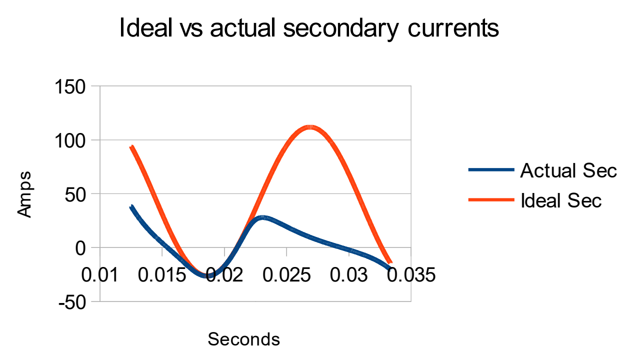


Case	17	18	19	20
True RMS Error	0%	1%	21%	46%
Filtered Fundamental Error	0%	0%	4%	28%
Peak Error	0%	0%	11%	40%

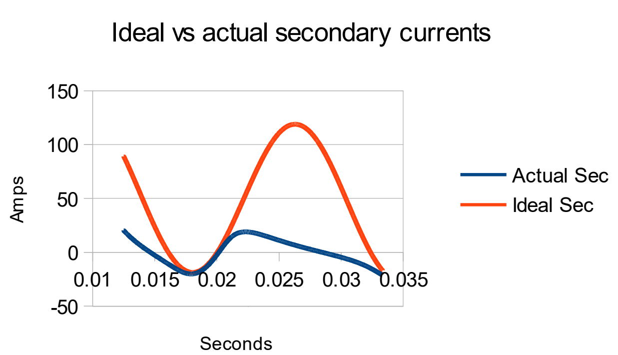
21



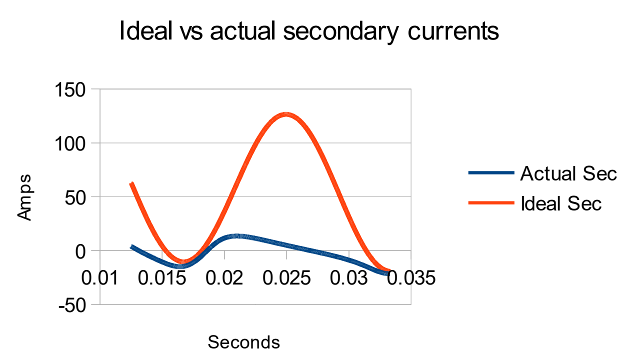
22



23



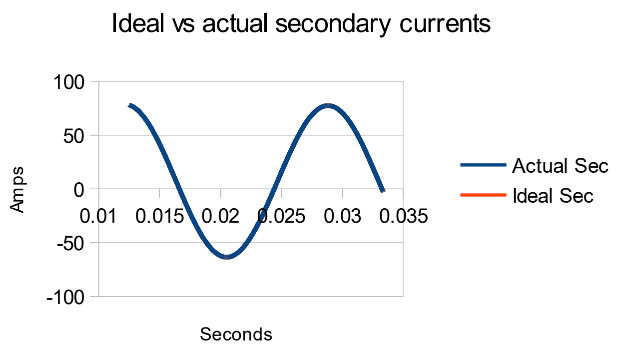
24



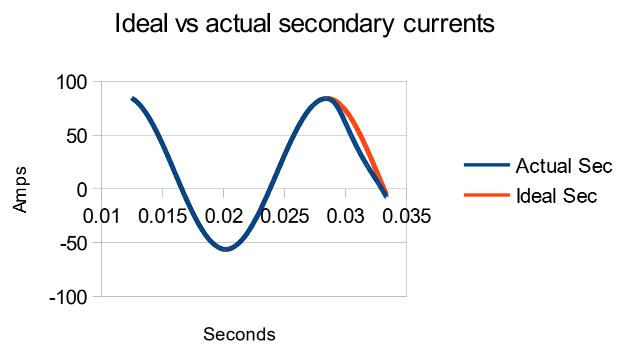
Case	21	22	23	24
True RMS Error	63%	74%	82%	86%
Filtered Fundamental Error	52%	68%	77%	83%
Peak Error	61%	75%	82%	83%

3ohm

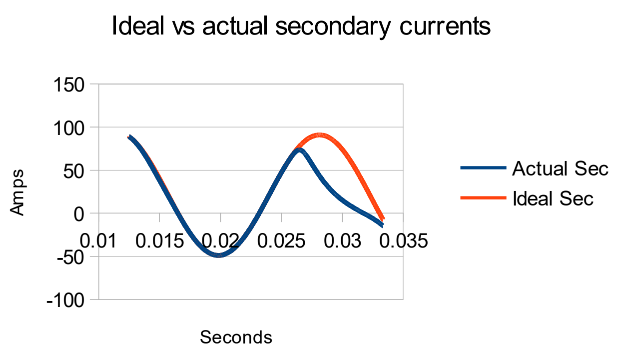
25



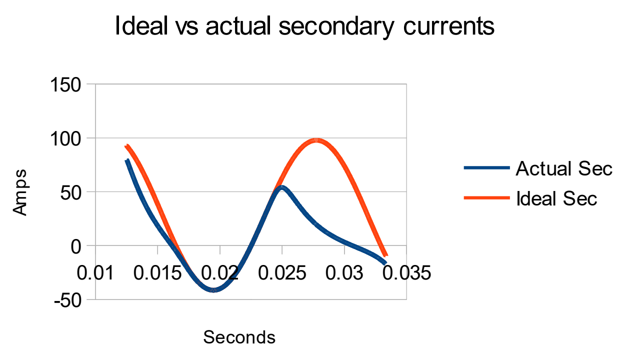
26



27

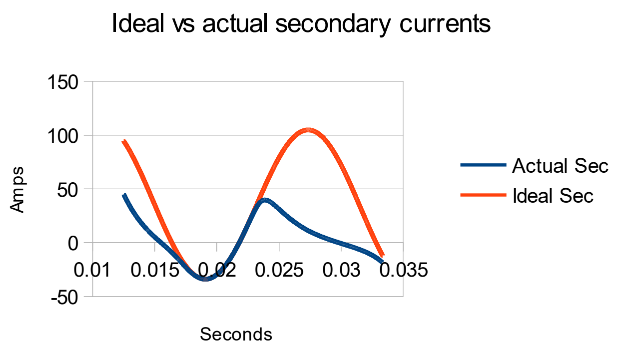


28

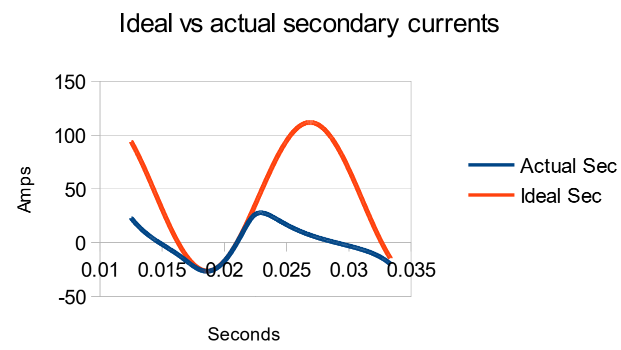


Case	25	26	27	28
True RMS Error	0%	5%	30%	50%
Filtered Fundamental Error	0%	1%	10%	37%
Peak Error	0%	0%	19%	45%

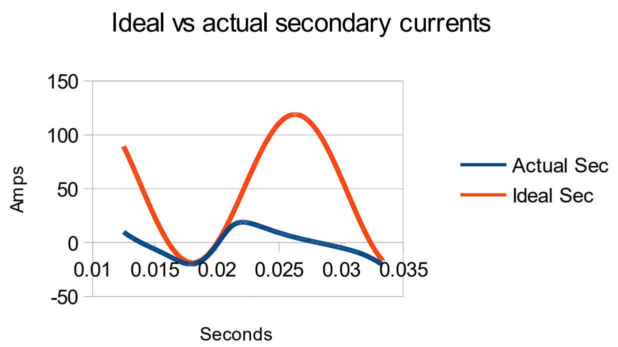
29



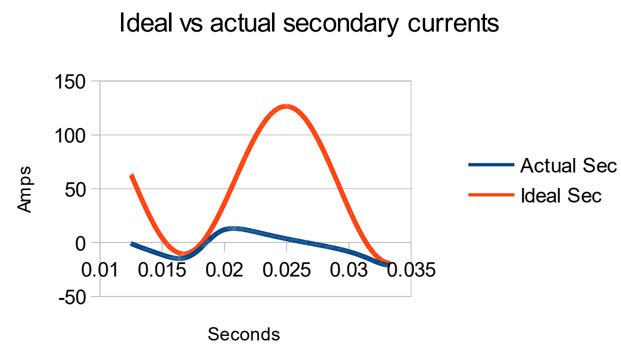
30



31

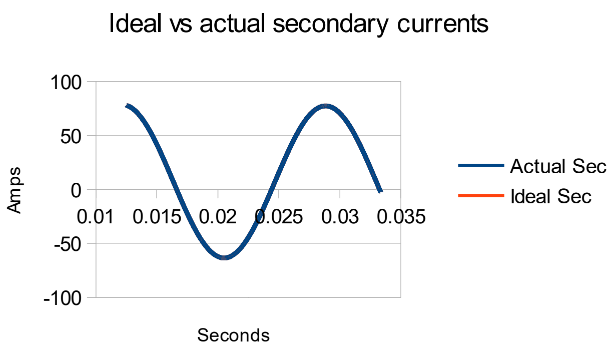


32

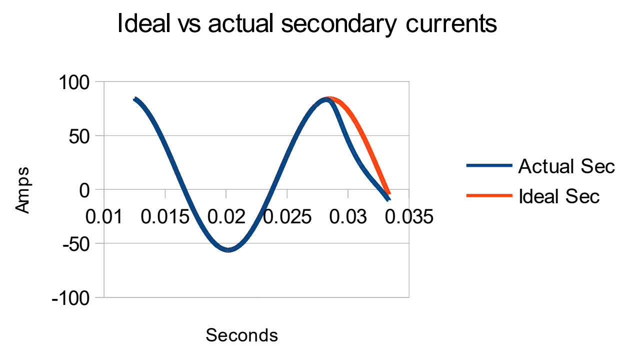


Case	29	30	31	32
True RMS Error	64%	75%	82%	87%
Filtered Fundamental Error	57%	71%	79%	83%
Peak Error	62%	75%	83%	84%

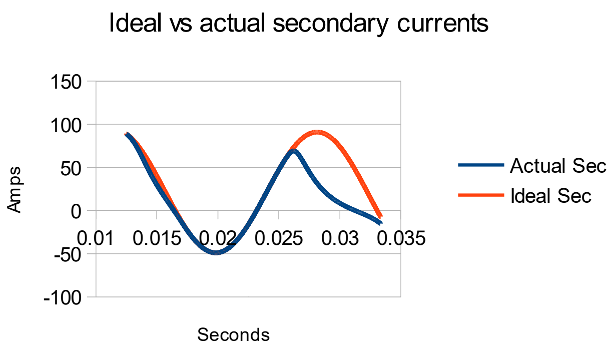
33



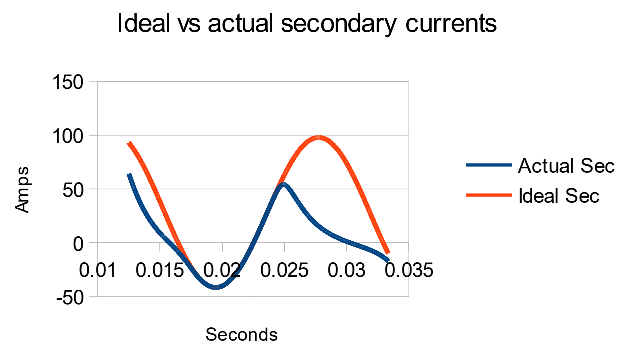
34



35

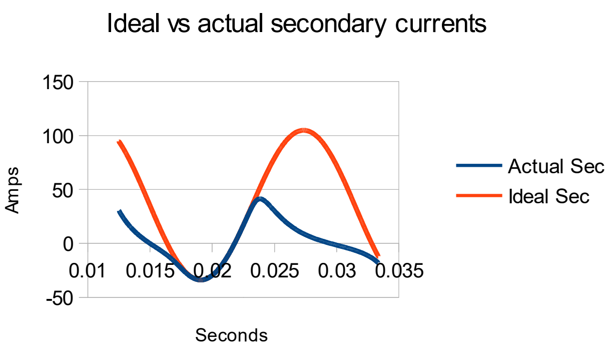


36

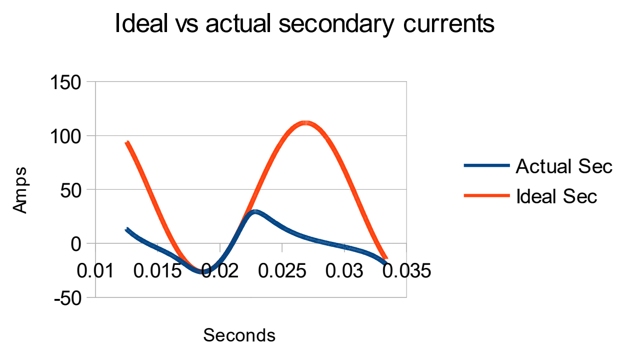


Case	33	34	35	36
True RMS Error	0%	10%	35%	52%
Filtered Fundamental Error	0%	2%	16%	43%
Peak Error	0%	1%	24%	45%

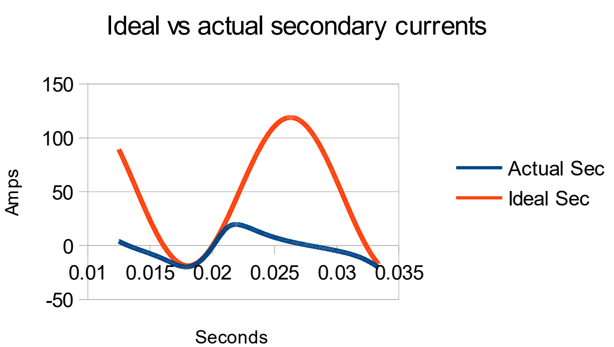
37



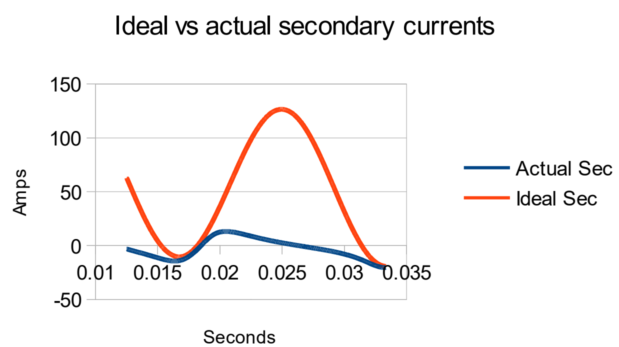
38



39



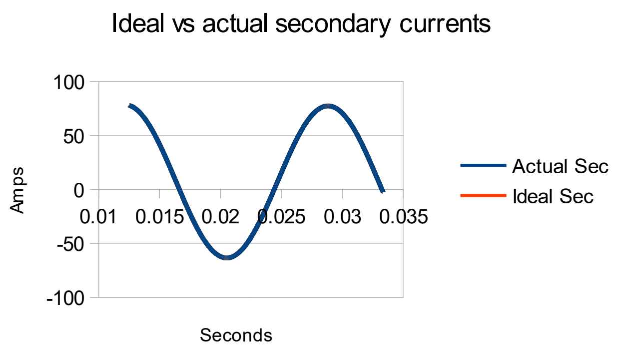
40



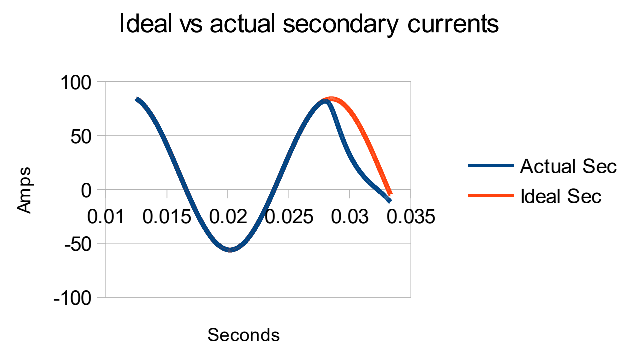
Case	37	38	39	40
True RMS Error	64%	75%	83%	87%
Filtered Fundamental Error	60%	72%	79%	84%
Peak Error	61%	74%	83%	84%

4ohm

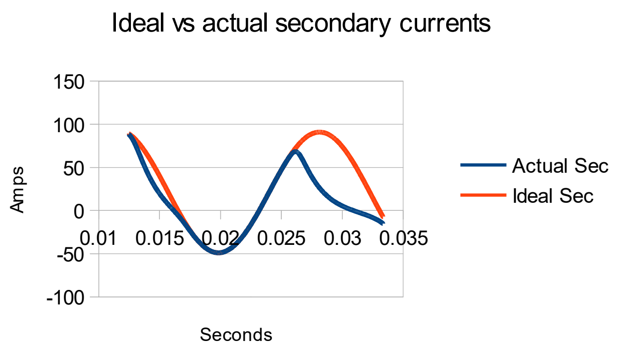
41



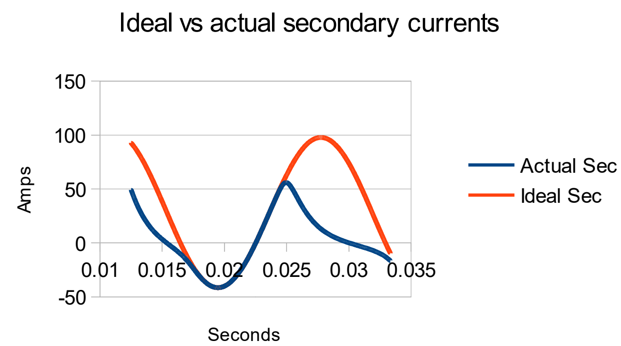
42



43

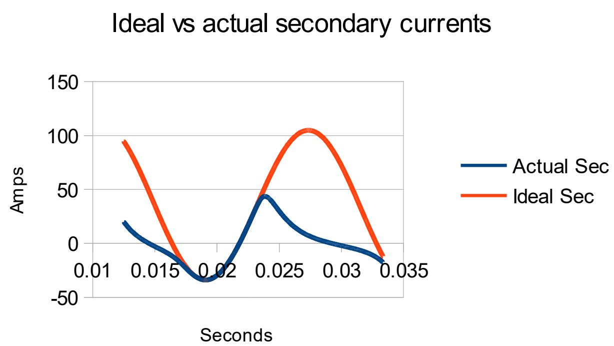


44

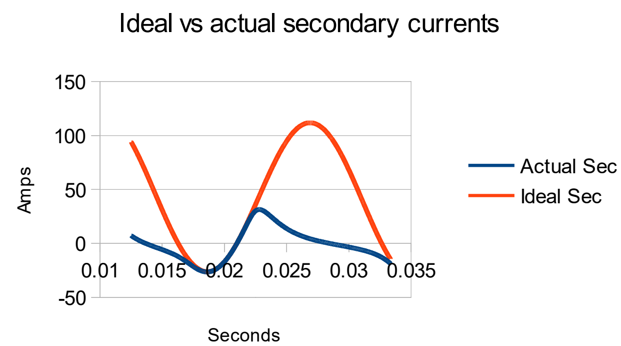


Case	41	42	43	44
True RMS Error	0%	14%	37%	52%
Filtered Fundamental Error	0%	1%	21%	46%
Peak Error	0%	3%	25%	43%

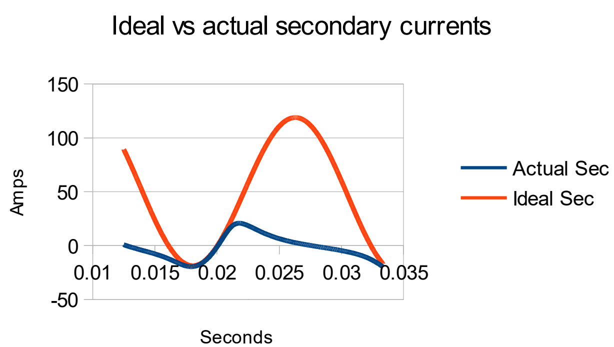
45



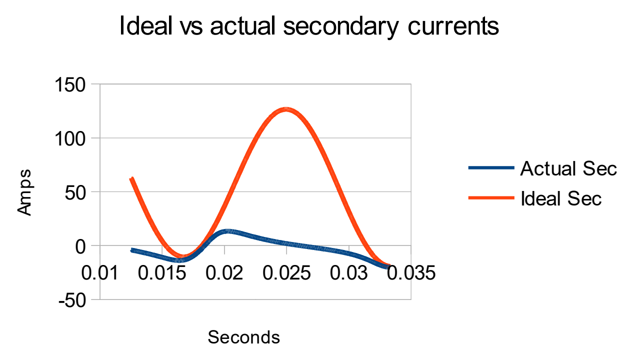
46



47

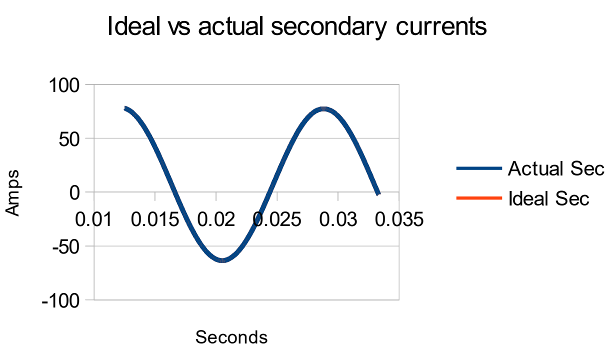


48

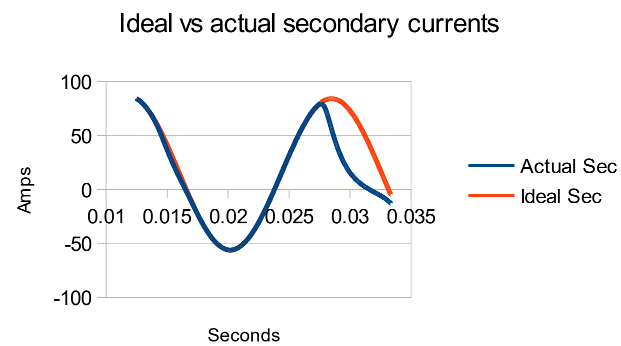


Case	45	46	47	48
True RMS Error	64%	75%	83%	88%
Filtered Fundamental Error	62%	73%	80%	85%
Peak Error	58%	72%	82%	84%

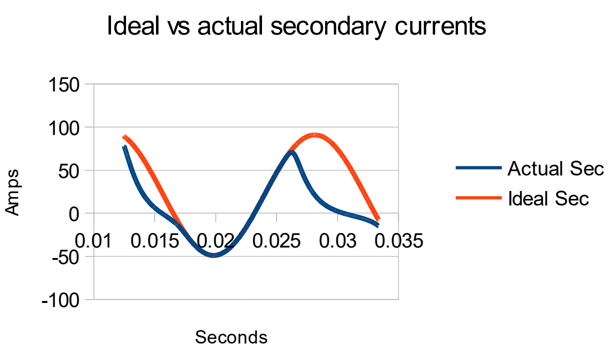
49



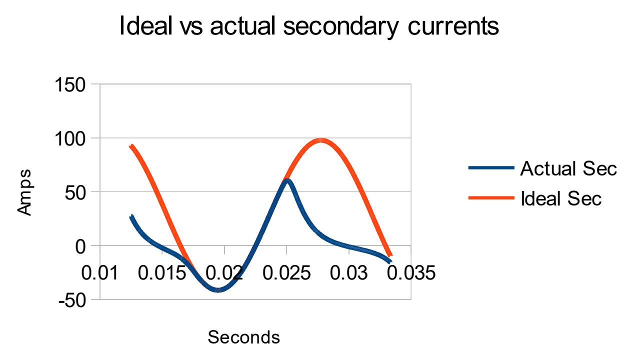
50



51

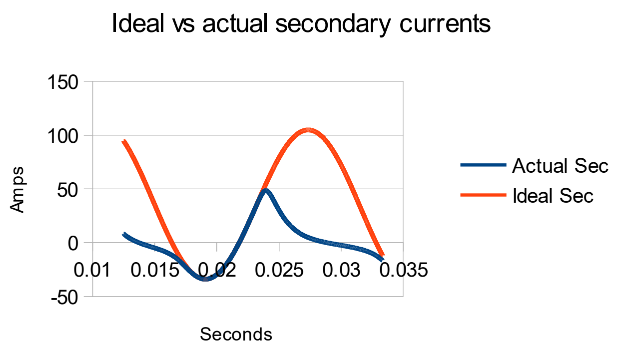


52

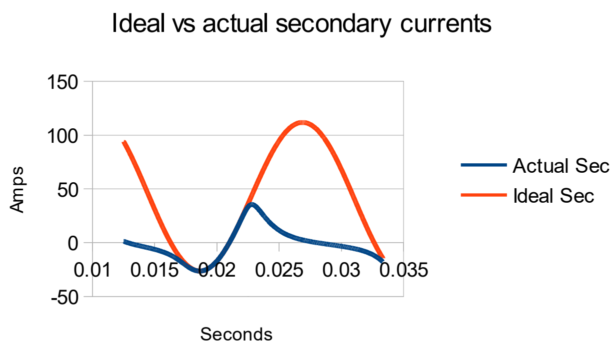


Case	49	50	51	52
True RMS Error	1%	20%	37%	51%
Filtered Fundamental Error	0%	2%	28%	50%
Peak Error	0%	6%	22%	38%

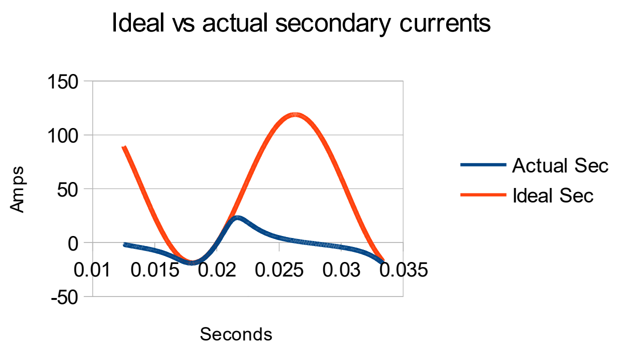
53



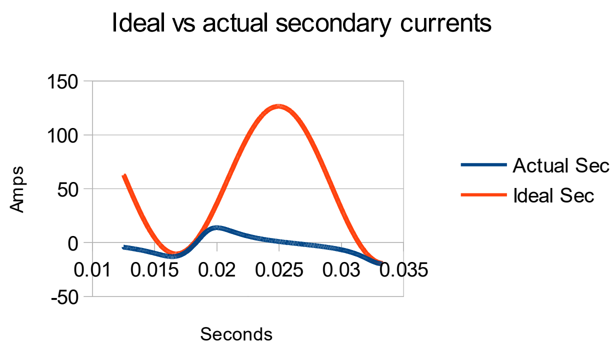
54



55



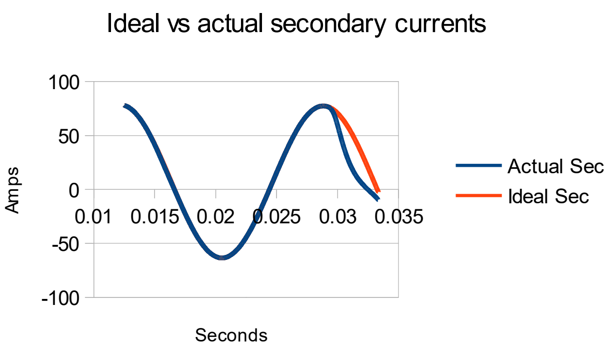
56



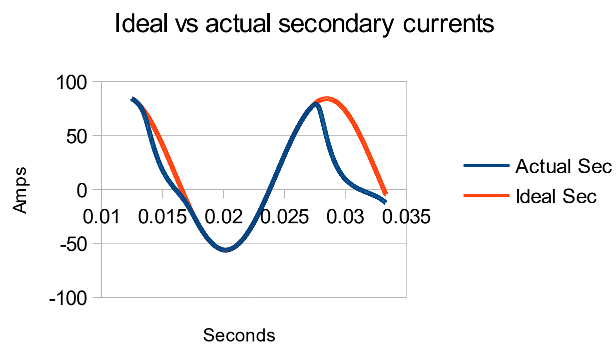
Case	53	54	55	56
True RMS Error	64%	75%	83%	88%
Filtered Fundamental Error	64%	74%	81%	86%
Peak Error	54%	68%	80%	85%

6ohm

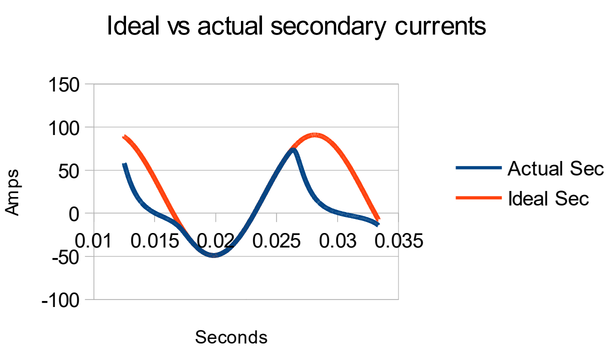
57



58



59



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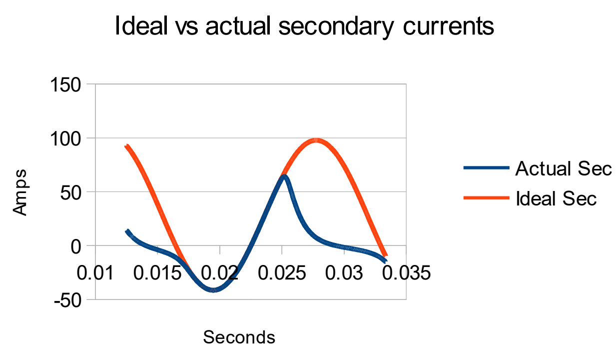
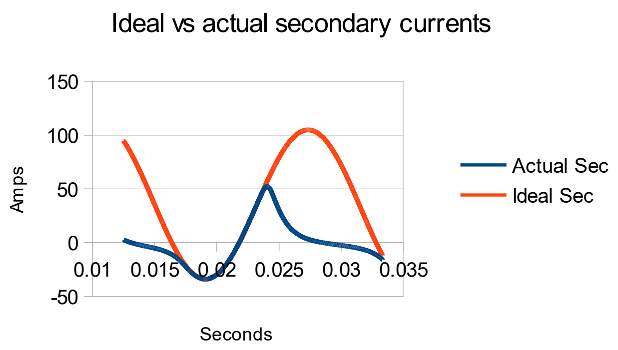
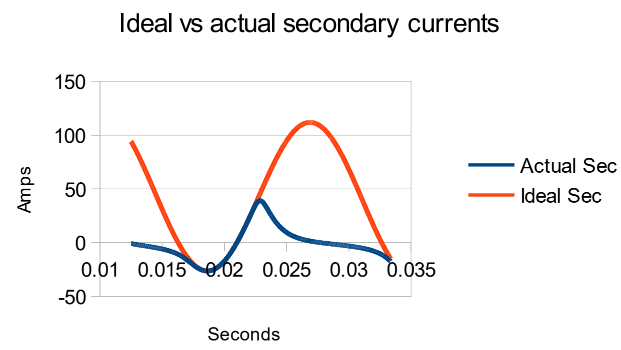


Case	57	58	59	60
True RMS Error	6%	22%	36%	50%
Filtered Fundamental Error	1%	6%	33%	51%
Peak Error	0%	6%	19%	34%

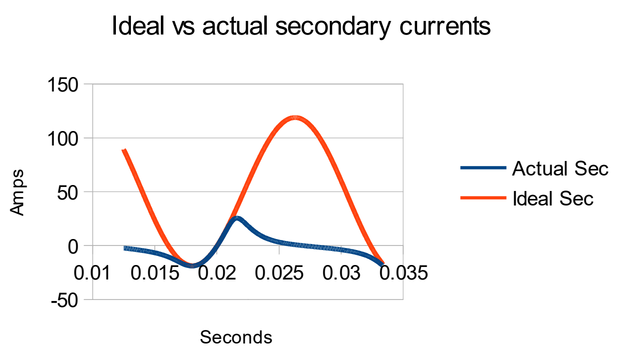
61



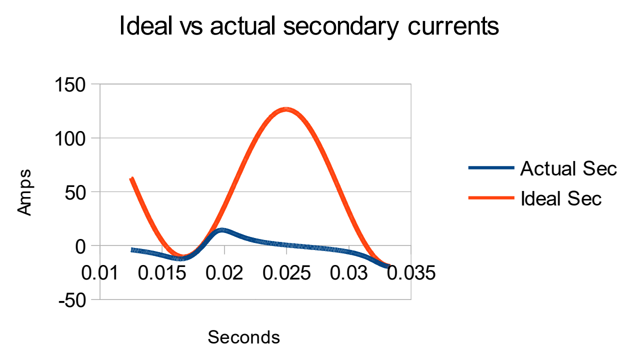
62



63



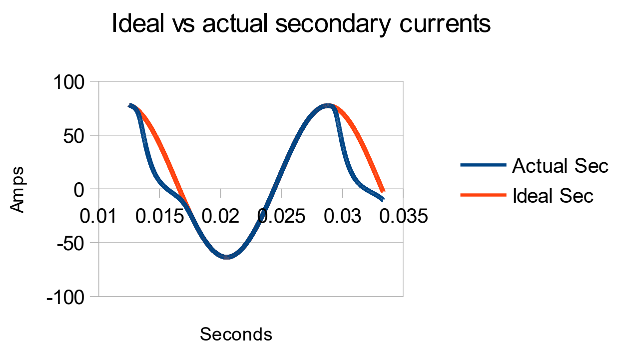
64



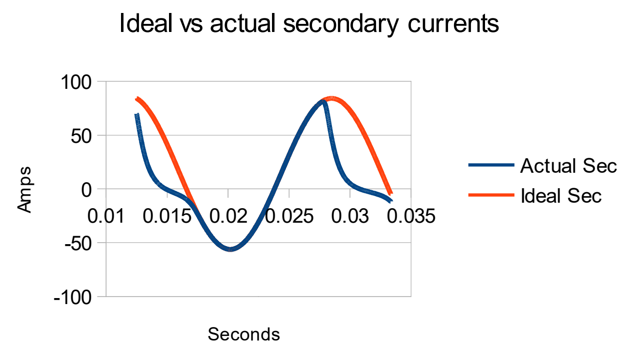
Case	61	62	63	64
True RMS Error	63%	74%	83%	89%
Filtered Fundamental Error	64%	74%	82%	87%
Peak Error	50%	65%	78%	85%

8ohm

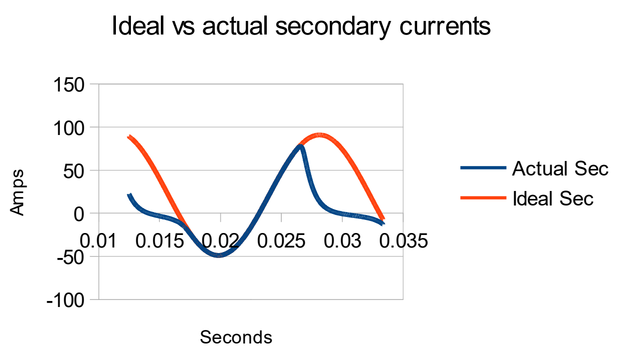
65



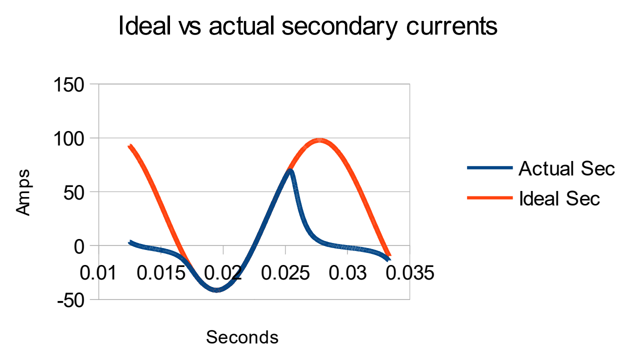
66



67



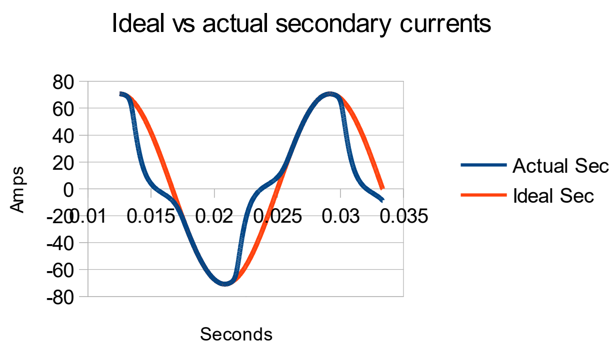
68



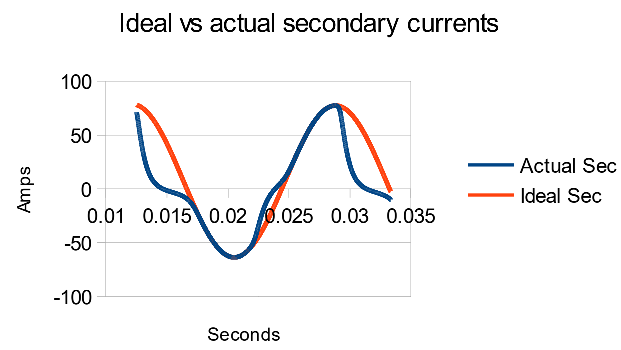
Case	65	66	67	68
True RMS Error	9%	21%	36%	50%
Filtered Fundamental Error	5%	19%	38%	53%
Peak Error	0%	4%	15%	29%

10

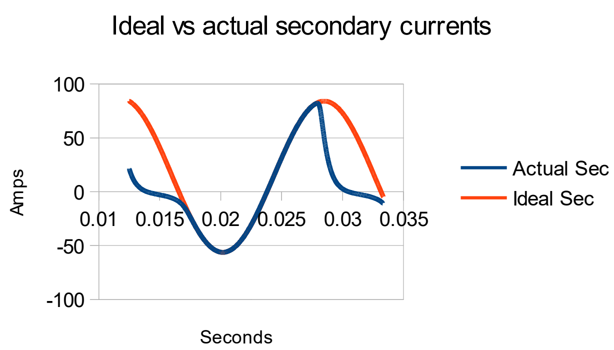
69



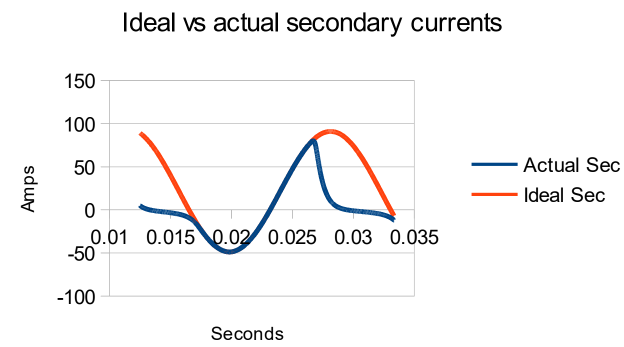
70



71

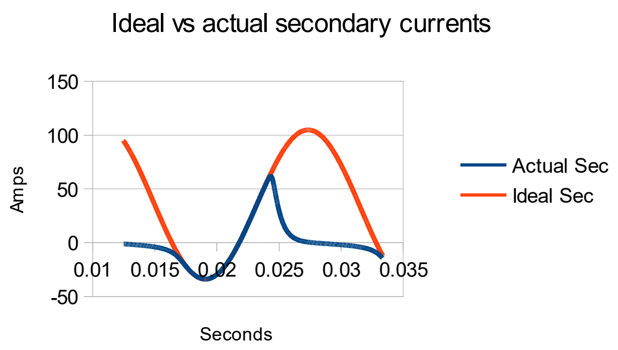


72

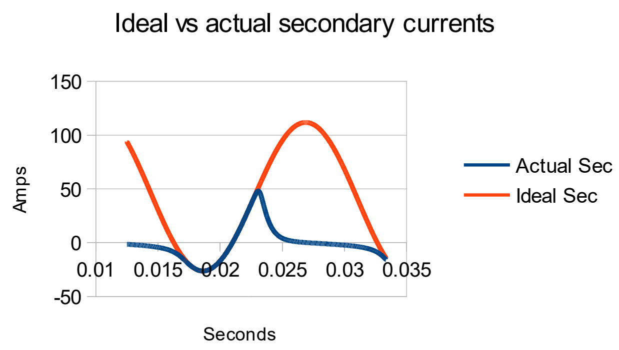


Case	69	70	71	72
True RMS Error	12%	13%	21%	39%
Filtered Fundamental Error	14%	16%	24%	35%
Peak Error	0%	0%	2%	12%

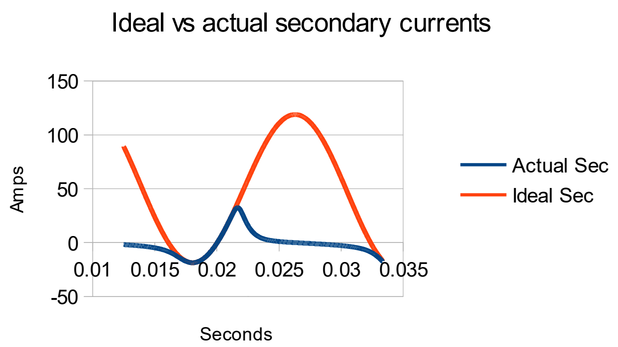
73



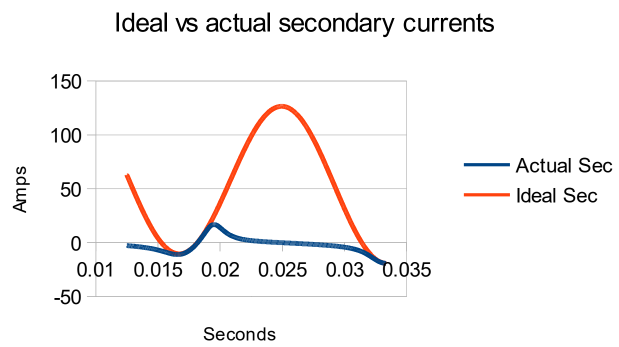
74



75

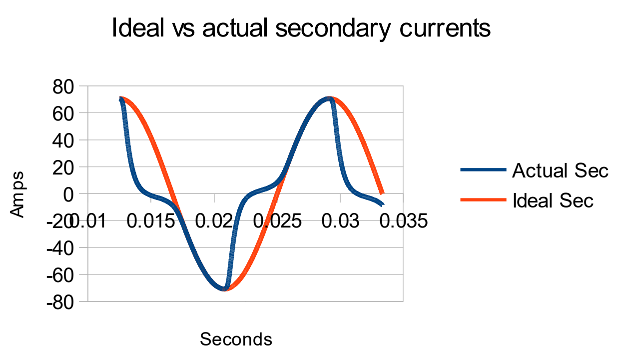


76

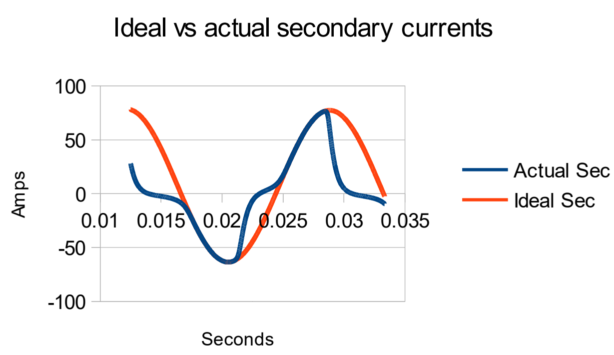


Case	73	74	75	76
True RMS Error	62%	74%	83%	90%
Filtered Fundamental Error	66%	76%	85%	90%
Peak Error	41%	57%	73%	85%

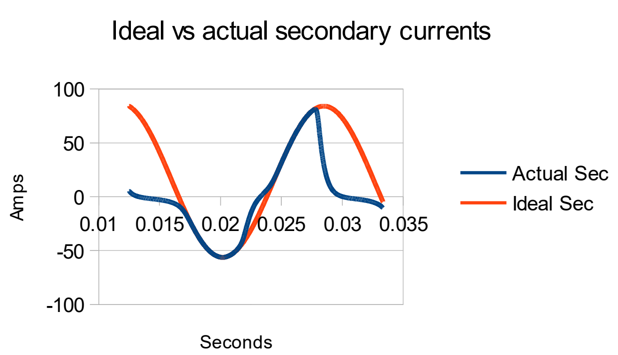
77



78



79



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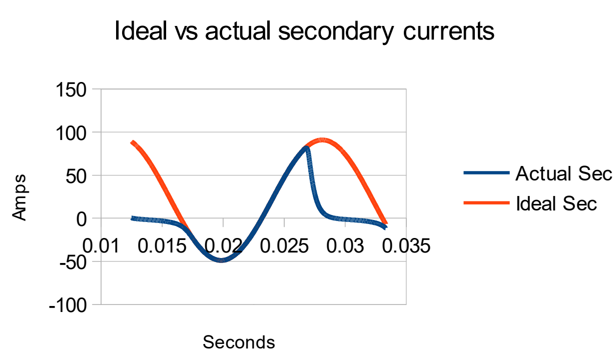
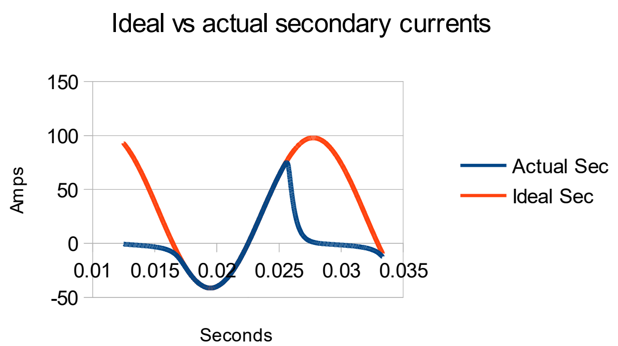
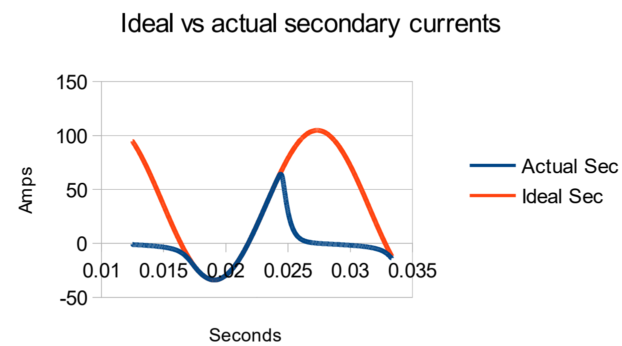


Case	77	78	79	80
True RMS Error	20%	21%	25%	35%
Filtered Fundamental Error	25%	27%	30%	40%
Peak Error	0%	1%	4%	10%

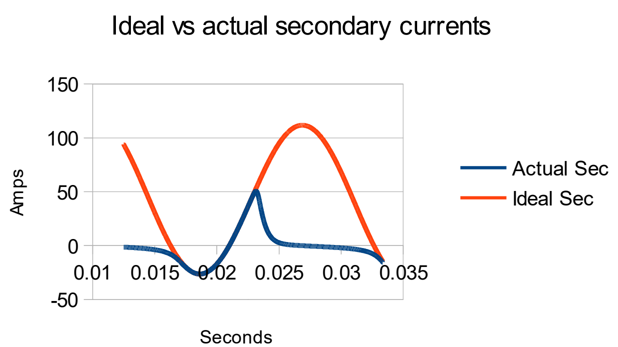
81



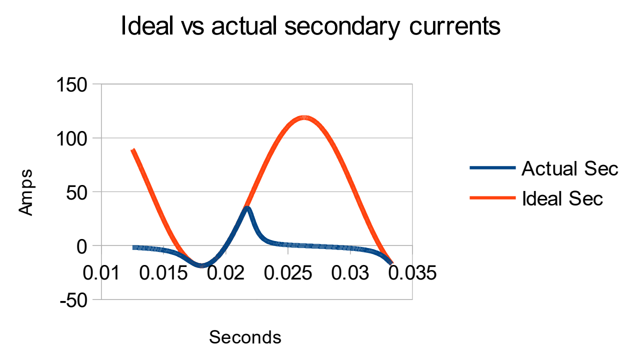
82



38

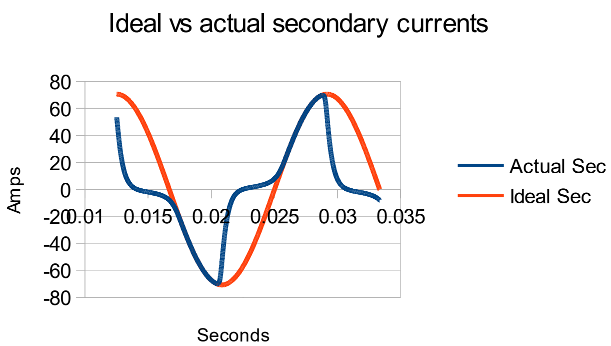


84



Case	81	82	38	84
True RMS Error	49%	62%	73%	83%
Filtered Fundamental Error	54%	67%	77%	85%
Peak Error	24%	39%	55%	71%

85



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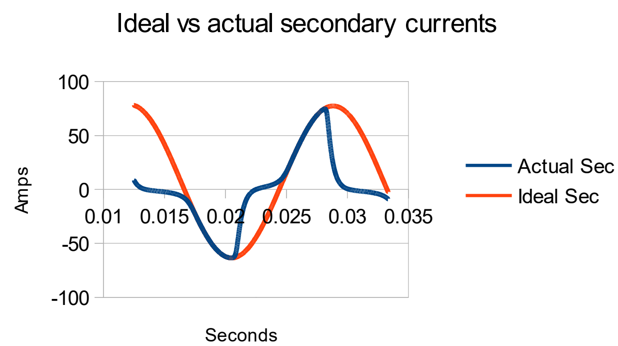
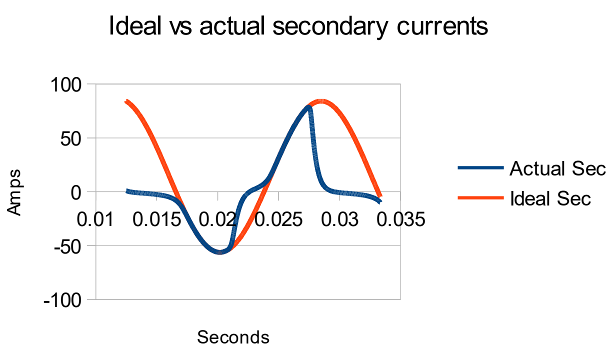
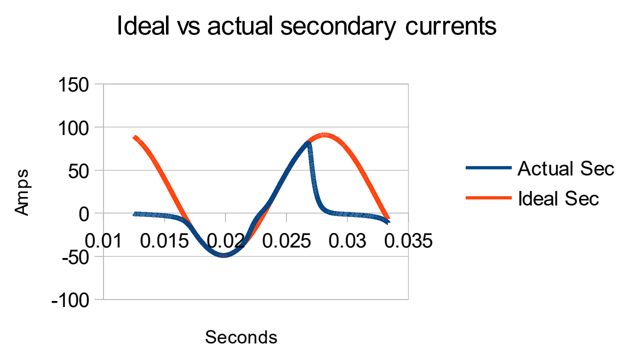


87

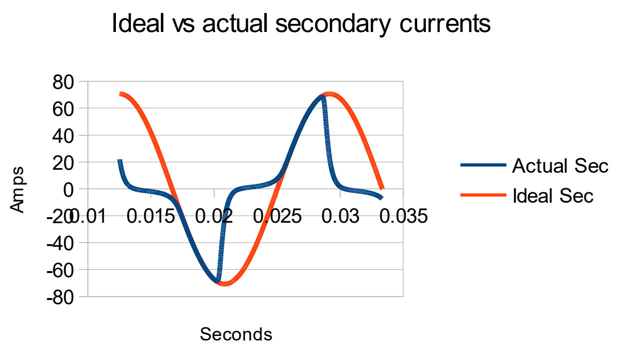


88

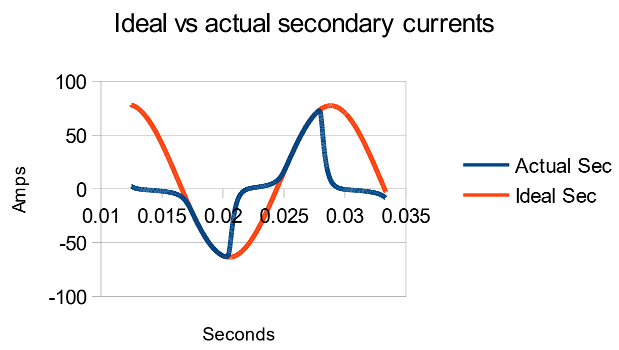


Case	85	86	87	88
True RMS Error	28%	28%	31%	36%
Filtered Fundamental Error	34%	35%	37%	42%
Peak Error	1%	4%	7%	11%

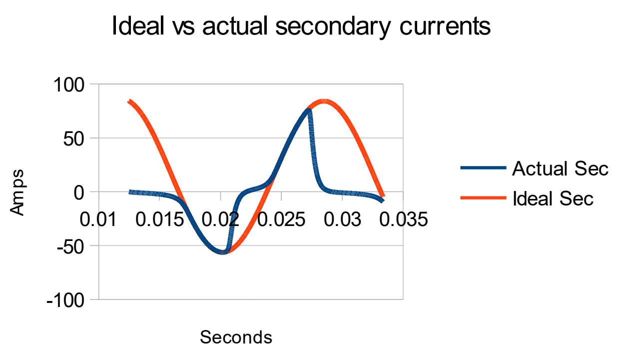
89



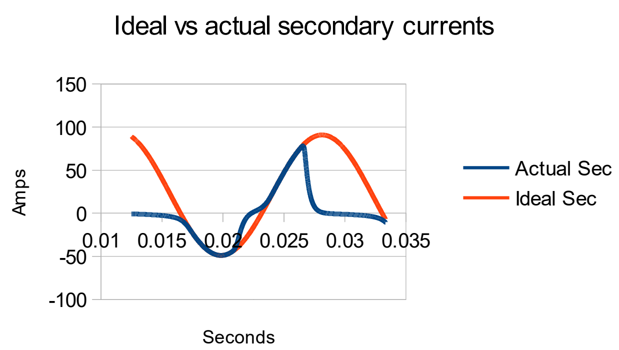
90



91

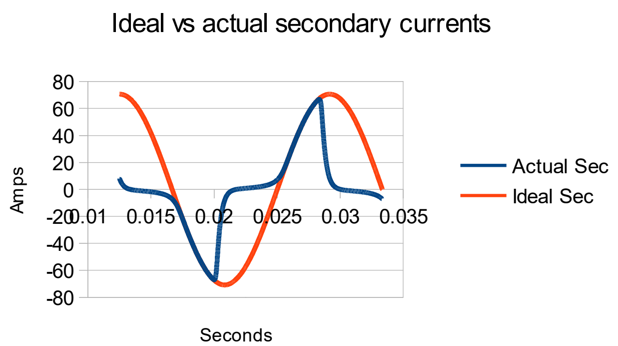


92

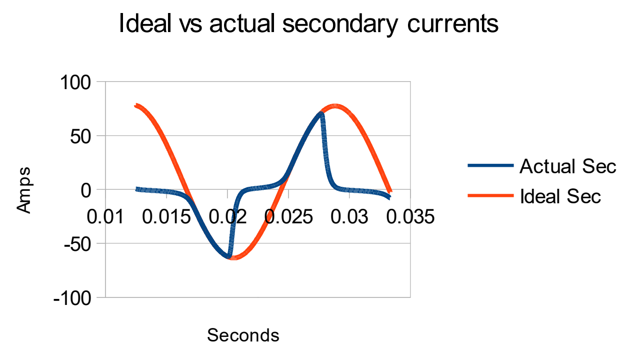


Case	89	90	91	92
True RMS Error	34%	34%	37%	40%
Filtered Fundamental Error	42%	42%	44%	47%
Peak Error	3%	6%	10%	14%

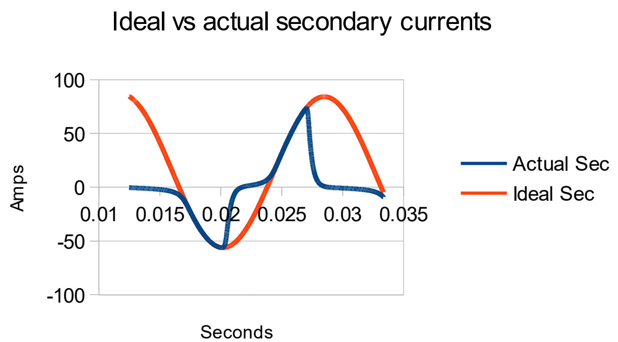
93



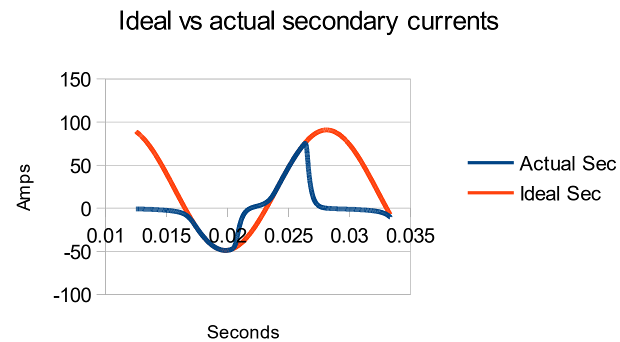
94



95



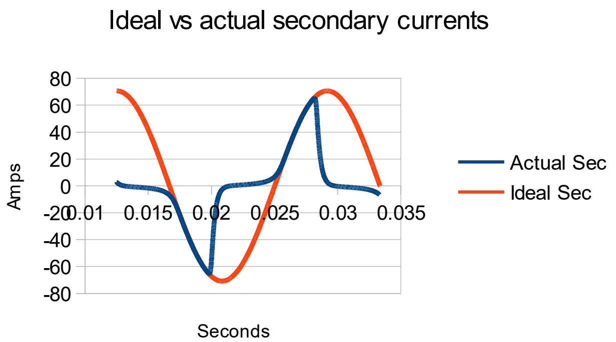
96



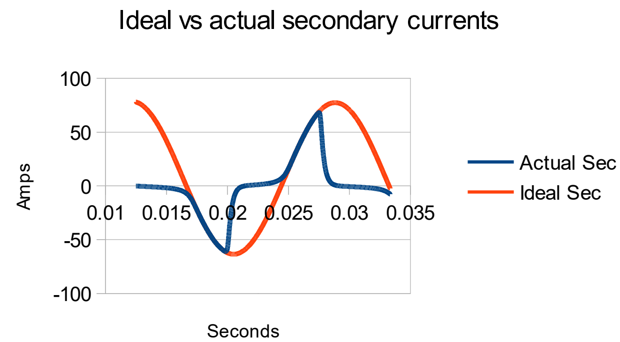
Case	93	94	95	96
True RMS Error	39%	39%	41%	45%
Filtered Fundamental Error	48%	48%	49%	52%
Peak Error	5%	9%	13%	17%

20

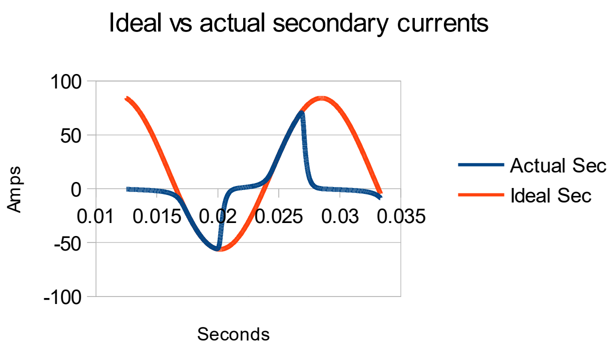
97



98



99



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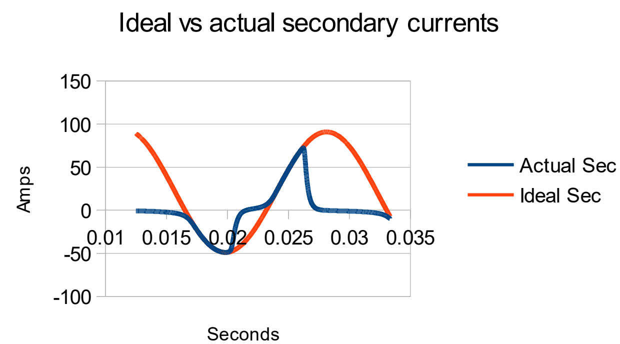
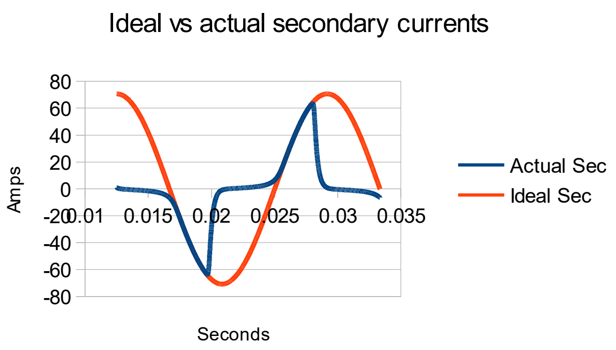
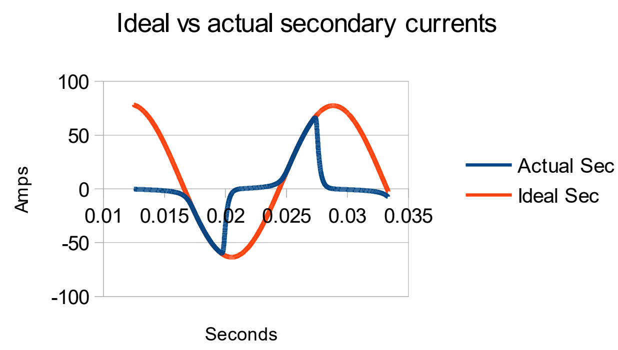


Case	97	98	99	100
True RMS Error	43%	43%	45%	48%
Filtered Fundamental Error	52%	53%	54%	56%
Peak Error	8%	12%	16%	21%

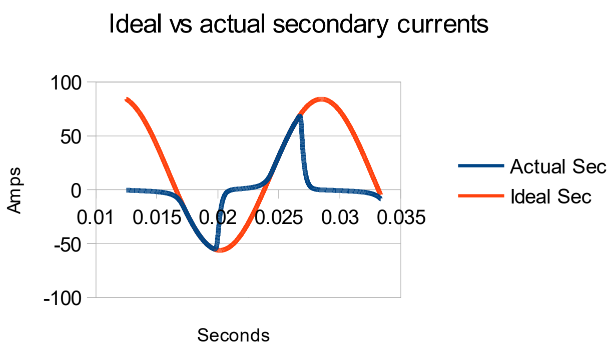
101



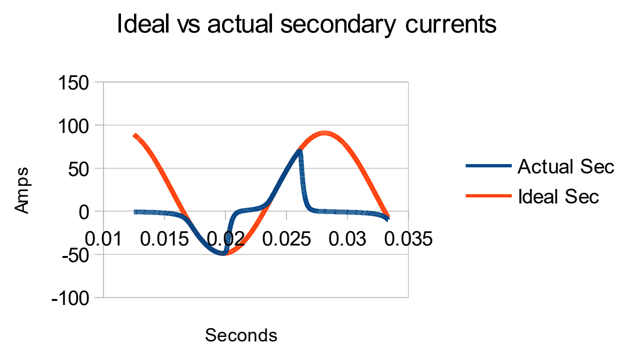
102



103

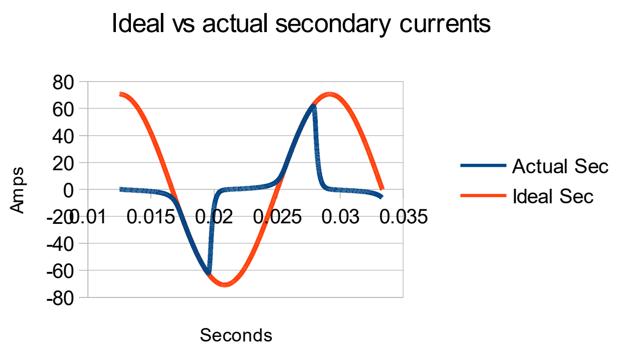


104

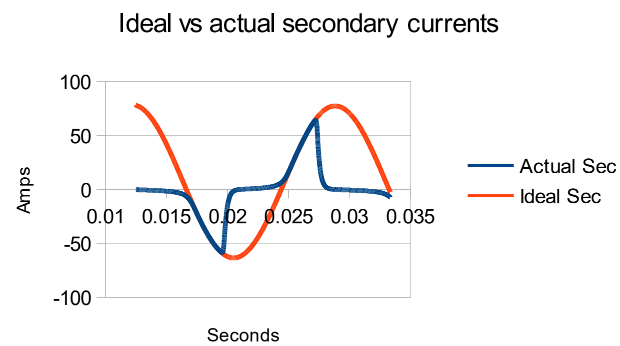


Case	101	102	103	104
True RMS Error	47%	47%	49%	51%
Filtered Fundamental Error	57%	57%	58%	59%
Peak Error	10%	15%	19%	23%

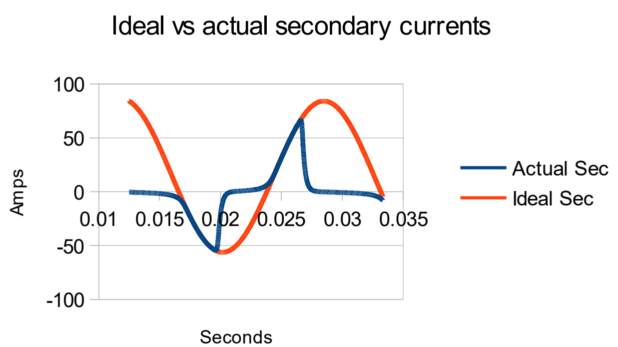
105



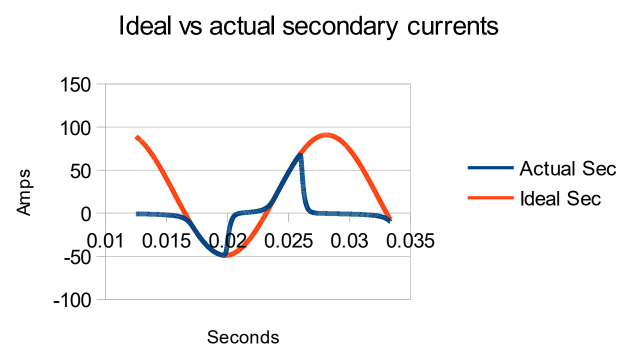
106



107



108



Case	105	106	107	108
True RMS Error	50%	50%	52%	54%
Filtered Fundamental Error	60%	60%	61%	63%
Peak Error	13%	17%	21%	26%