Computing the heat losses of AC motor and AC drive

The motivation for loss computing in DriveSize is smart engineering and speeding up the engineering process. Now customers can compute the heat losses by themselves for their drive component selection choices and for their applications and include this information in their decision process. The purpose of this document is to convince that the losses are computed accurately enough for engineering purposes.

Computing the losses of motors

The computing is done for standard and HXR, AMA, AMI motors.
From mechanical speeds the relative speed n' and field weakening point is determined based on field weakening value of selected drive (92%....100%).

Up to the field weakening point the relative motor currents are computed according to:

$$I_{\mathrm{sd}}' = \sin\varphi_{\mathrm{n}} + \cos\varphi_{\mathrm{n}} \left[\sqrt{\left(\frac{T_{\mathrm{maxmot}}}{T_{\mathrm{n}}}\right)^2 - 1} - \sqrt{\left(\frac{T_{\mathrm{maxmot}}}{T_{\mathrm{n}}}\right)^2 - \left(\frac{T_{\mathrm{load}}}{T_{\mathrm{n}}}\right)^2} \right]$$

$$I_{\mathrm{sq}}' = \sqrt{\left(\frac{T_{\mathrm{load}}}{T_{\mathrm{n}}} \cos\varphi_{\mathrm{n}}\right)^2 + r}$$

$$I_{\mathrm{m}} = In * \sqrt{I_{\mathrm{sq}}'^2 + I_{\mathrm{sd}}'^2}$$

I_m =motor current
I_n =motor nominal current
Tn *=motor nominal torque*
Tmaxmot *=motor nominal max torque*
Tload *=load torque*
cosφn *=motor power factor at nominal speed*
sinφn = $\sqrt{1 - \cos\varphi_{\mathrm{n}}^{\ 2}}$
Isd' *=relative inductive current component*
Isq' *=relative active current component*
r *= riple factor constant*

On the field weakening area the same currents:

$$I_{\mathrm{sd}}' = \frac{1}{n'} \left(\sin\varphi_{\mathrm{n}} + \cos\varphi_{\mathrm{n}} \sqrt{\left(\frac{T_{\mathrm{maxmot}}}{T_{\mathrm{n}}}\right)^2 - 1} \right) - \cos\varphi_{\mathrm{n}} \sqrt{\left(\frac{T_{\mathrm{maxmot}}}{T_{\mathrm{n}}} \frac{1}{n'}\right)^2 - \left(\frac{T_{\mathrm{load}}}{T_{\mathrm{n}}} \frac{n'}{}\right)^2}$$

$$I_{\mathrm{sq}}' = \sqrt{\left(\frac{T_{\mathrm{load}} * n}{T_{\mathrm{n}} * n_{fwp}}\right)^2 + r}$$

$$I_{\mathrm{m}} = In * \sqrt{I_{\mathrm{sq}}'^2 + I_{\mathrm{sd}}'^2}$$

n =speed of the load point

n_{fwp} =motor field weakening speed

n' =n/ n_{fwp}

The rated losses of a motor:

$$Rtdlosses = (\frac{1}{\eta} - 1) * Pn$$

η =nominal efficiency

P_{n} =motor nominal shaft power. For NEMA motors P_{n} has to be converted first from HP to kW.

For standard motors DriveSize knows following in addition to the catalogue values:
1) stator resistance (at room temperature) Resuv
2) the no load current Inoload [A] and
3) no load losses Pnoload [W].

Computing relative loss proportions with sinusoidal supply

The distribution of iron, stator copper, rotor copper, additional and ventilation losses are computed. The total sum of these is 100%.

The resistance value is converted from room temperature into normal running temperature and to represent all three phases

$$R_{resuv} = R_{resuv} * 3/2 * (1 + \Delta\theta / 255)$$

If the motor is of existing type some assumptions are made like:

Resuv = 1%
Pnoload = 50%*RtdLosses
Inoload = 40%*In
Δθ = 80 (B) or 105 (F)

For HXR, AMA, AMI motors the iron, copper stator, copper rotor, additional and ventilation losses are given Pfe,Pcus, Pcur,Padd and Prho.

Losses in copper, stator

$Pcs = Resuv*In^2$

Friction losses, mostly ventilation

The multiplier for ventilation losses is picked from table.
Prh = kprh*Pnoload

Poles	IECH	IECH	IECH
	63…..100	112….250	280…**710**
2	0.45	0.55	0.6
4	0.15	0.3	0.3
6….12	0.14	0.2	0.25

Iron losses

Using Pnoload and Inoload and Prh
Pfe = Pnoload - Prh - Resuv*Inoload

Additional losses

Padd = 0,025*1000*Pn[kW]/RtdEff% for Pn <=1 kW
Padd = (0.025-0.005log10(Pn[kW]))*1000*Pn[kW]/RtdEff%
Padd = 0.005*1000*Pn[kW]/RtdEff if for Pn> 10000kW

Rotor copper losses

Pcr = (Pn/RtdEff - Pcs - Pfe)* (1-RtdSpeed*Poles/(fn*120))

Total losses

Psum = Pfe+Pcs+Pcr+Padd+Prh

Relative proportions of different losses

fe =Pfe/Psum
cs =Pcs/Psum
cr =Pcr/Psum
add=Padd/Psum
rh =Prh/Psum

The relative losses under fwp is computed for IC411, IC81W, IC611 motors

$$P' = fe*(0.7*f'+0.3*f'^{2}+kfe)+cs*\mathrm{Im}'^{2}+cr*kcr*(Isq'/\cos\varphi_n)^{2}$$
$$+add*\mathrm{Im}'^{2}*(0.6*f'+0.4*f'^{1.65})+rh*f_n'^{2.8}$$

and for IC416, IC86W, IC666 and other models

$$P' = fe*(0.7*f'+0.3*f'^{2}+kfe)+cs*\mathrm{Im}'^{2}+cr*kcr*(Isq'/\cos\varphi_n)^{2}$$
$$+add*\mathrm{Im}'^{2}*(0.6*f'+0.4*f'^{1.65})+rh$$

where f’=f/f_n

Over fwp the relative loss equation is for IC411, IC81W, IC611 motors

$$P' = fe*(0.7/f'+0.3+kfe)+cs*\mathrm{Im}'^{2}+cr*kcr*(Isq'/\cos\varphi_n)^{2}$$
$$+add*\mathrm{Im}'^{2}*(0.6*f'+0.4*f'^{1.65})+rh*f_n'^{2.8}$$

and for IC416, IC86W, IC666 and other models

$$P' = fe*(0.7/f'+0.3+kfe)+cs*\mathrm{Im}'^{2}+cr*kcr*(Isq'/\cos\varphi_n)^{2}$$
$$+add*\mathrm{Im}'^{2}*(0.6*f'+0.4*f'^{1.65})+rh$$

where f’=f/f_{wp} and f_n’= f/f_n and HXR, AMA, AMI motors f’=f’$_n$
and where *kfe* is additional iron loss and *kcr* is rotor multiplier.

The total heat losses [W] of motor(s) is computed considering also the number of parallel motors:

$$Plm = Rtdlosses*P'*Nmotors$$

The motor losses are calculated at torques 25%, 50%, 75%, 100% and 125% for constant torque and power load types.

1. min speed (if min speed < 0.2*base speed then min speed = 0.2*base speed)
2. (base – min)/2 + min
3. base speed
4. (max – base)/2 + base, (when needed)
5. max speed , (when needed)

	25%	50%	75%	100%	125%
1					
2					
3					
4					
5					

For Pump&Fan loads the speeds are: 20%, 40%, 60%, 80% and 100% and torques according to following table. If load is really quadratic the values on diagonal (marked with X) represent the losses but as we now the real pump/fan loads deviate from the ideal model and that is why a table is given. To get the final result application engineer may need to interpolate the final answer by utilizing the given grid. The DrivePump product from ABB will do this automatically for pumps.

Losses of motor(s) [W]:

	4%	16%	36%	64%	100%
1	X				
2		X			
3			X		
4				X	
5					X

Computing heat losses for AC drives

The following description is only for single AC drives having a diode bridge as rectifier and IGBT inverter. The low-harmonic and regenerative drives are different and more complicated. Then also the power flow is exclusively from grid to motor and efficiency computing is simple.

The total heat losses are sum of no-load losses, possible choke losses and the losses of IGBT and freewheeling diodes and rectifier diodes. The no-load losses (P_{L_noload}) are assumed to be constant. The losses of IGBT module (P_{tot_module}) are calculated for each load point. The number of parallel IGBT-modules N is considered. This means that total losses of IGBT is multiplied by 6 and by N. When computing P_{tot_module} a constant switching frequency is assumed, this is 3 or 2 kHz depending on drive type.

Single Drive losses are calculated at same load points as for motor so that adding them up is easy. If losses are shown as function of frequency it is not a customer friendly way.

Calculation of modulation index and power factor

The modulation index below field weakening point:

$$M = \frac{f_s}{f_{field\_weak\_point}}$$, where

f_s = output frequency

$f_{field\_weak\_point}$ = field weakening frequency which depends on motor, dc-voltage etc.

The power factor (Cos φ) calculation is based on stator current and active current component:

$$Cos\varphi = \frac{I_{sq}}{I_m}$$, where

I_{sq} = active current component

I_m = stator current

Calculation of on-state losses

On-state losses of inverter semiconductors are calculated by using well known equations:

$$P_{on\_igbt} = \frac{U_{ce0} \cdot \hat{I}_v}{2} \cdot \left(\frac{1}{\pi} + \frac{M \cdot \cos\varphi}{4} \right) + r_{ce} \cdot \hat{I}_v^{\,2} \cdot \left(\frac{1}{8} + \frac{M \cdot \cos\varphi}{3 \cdot \pi} \right)$$

$$P_{on\_diode} = \frac{U_{f0} \cdot \hat{I}_v}{2} \cdot \left(\frac{1}{\pi} - \frac{M \cdot \cos\varphi}{4} \right) + r_f \cdot \hat{I}_v^{\,2} \cdot \left(\frac{1}{8} - \frac{M \cdot \cos\varphi}{3 \cdot \pi} \right)$$

where

P_{on_igbt} = on-state losses of IGBT

P_{on_diode} = on-state losses of diode

$\hat{I}_v$ = peak value of output phase current divided by N

And the rest are the parameters of semiconductor for the inverter.

Calculation of switching losses

Switching losses of inverter semiconductors:

$$P_{sw\_igbt} = coefisw \cdot Udc \cdot \hat{I}_v \cdot fsw \cdot coefdudt / \pi$$

$$P_{sw\_diode} = coefdsw \cdot Udc \cdot \hat{I}_v \cdot fsw / \pi$$

where

$P_{\text{sw\_igbt}}$ = switching losses of IGBT
$P_{\text{sw\_diode}}$ = switching losses of diode
$U\text{dc}$ = voltage of dc-capacitor
$\hat{I}_\text{v}$ = peak value of phase current
coefisw = sw energy of IGBT divided by voltage and current
fsw = average of switching frequency
coefdsw = sw energy of diode divided by voltage and current
coefdudt = type dependent coefficients.

Calculation of rectifier losses and resistive losses

DC or AC-chokes are used depending on the type of frequency converter and the U_{dc} varies a little due to that. Then dc and ac currents are computed

If DC choke is used

$$U_{dc} = 1.35 * U_{line} + 1.7$$

and if AC chokes are used then little lower

$$U_{dc} = 1.35 * 0.992 * U_{line} + 1.7$$

$$I_{dc} = \frac{P_{inu\_out}}{U_{dc}}$$

$$I_{ac} = 0.89 \cdot I_{dc}$$

$$P_{inu\_out} = Pload + Plm$$

where

$P_{\text{inu\_out}}$ = output power of inverter
I_{dc} = dc current
I_{ac} = line side ac current
P_{load} = mechanical power load at calculation point
P_{lm} = Power losses of motor at load point.

The resistive losses are computed based on coefficient R_{LLmax} (mostly choke) which is a drive type dependent constant combining all resistive losses.

If DC choke

$$P_{LL} = I_{dc}^2 \cdot R_{LL\max}$$

If AC choke

$$P_{LL} = I_{ac}^2 \cdot R_{LL\max}$$

The average and rms currents of branch are calculated

$$I_{ave} = 0.333 * I_{dc}$$

if DC choke

$$I_{rms} = 0.60 * I_{dc}$$

If AC choke

$$I_{rms} = 0.63 * I_{dc}$$

The losses of rectifier:

$$P_{on\_rectifier\_d} = U_{0R} \cdot I_{ave} + r_R \cdot I_{rms}^2$$

$$P_{tot\_rectifier} \approx 6 * P_{on\_rectifierd}$$

where $P_{\text{on\_rectifier\_d}}$ = on-state losses of rectifier diode
$P_{\text{totrectifier}}$ = total losses of rectifier
U_{0R} = threshold voltage [V]
r_R = differential resistance [Ω]

Total losses and reporting

Total losses are calculated at the same load points than on-state losses:

$$P_{tot\_\mathrm{mod}ule} = (P_{on\_igbt} + P_{sw\_igbt} + P_{on\_diode} + P_{sw\_diode}) * 6$$

The total losses of frequency converter:

$$P_{tot} = N * P_{tot\_\mathrm{mod}ule} + P_{tot\_rectifier} + P_{LL} + P_{L\_noload}$$

In DriveSize the drive losses are calculated at motor torques 25%, 50%, 75%, 100% and 125% for constant torque and power load types.

1. min speed (if min speed < 0.2*base speed then min speed = 0.2*base speed)
2. (base – min)/2 + min
3. base speed
4. (max – base)/2 + base, (when needed)
5. max speed , (when needed)

	25%	50%	75%	100%	125%
1					
2					
3					
4					
5					

For Pump&Fan loads the speeds are: 20%, 40%, 60%, 80% and 100% and torques according to following table.

Losses of motor(s) [W]:

	4%	16%	36%	64%	100%
1					
2					
3					
4					
5					

Also the overall efficiency at base speed is shown for single drives.

The last thing is the worst case losses, which is computed by multiplying motor loss values by 1.10 or 1.15 according to IEC standard having the power limit at 150 kW.
At partial loads the losses are multiplied at least with 1.2.

The drive losses are multiplied by 1.10 and then the worst case losses are computed by adding together the worst motor and worst drive losses. The idea of worst case losses is explained in another DriveSize document: AC Drive efficiency and loss estimation.